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Research Plans for Improving Understanding of Effects of Very Low-Frequency Noise of Heavy Lift Rotorcraft

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1. INTRODUCTION AND BACKGROUND

1.1 Purpose and organization of report

This report reviews the English-language technical literature on infrasonic and low-frequency[1] noise effects; identifies the most salient effects of noise produced by a future large civil tiltrotor[2] aircraft on crew, passengers, and communities near landing areas; and recommends research needed to improve understanding of the effects of such noise on passengers, crew, and residents of areas near landing pads.

The consequences of onboard, airport, and community exposure to infrasonic and low-frequency noise produced by tiltrotor operations are uncertain for several reasons. The circumstances of onboard and residential exposure to tiltrotor noise will not closely resemble continuous, long-term exposure to infrasound and low-frequency noise in industrial or occupational settings, nor the common conditions of exposure to low-frequency noise from road and rail traffic, nor from ventilation systems. Furthermore, because interest in the effects of noise on individuals and communities has historically centered on readily-audible, higher-frequency transportation noise, the effects of low-frequency and infrasonic noise are less thoroughly documented.

After introductory discussions of expected levels and circumstances of exposure to tiltrotor noise, Section 2 of this report describes the technical literature on effects of infrasound and low-frequency noise on individuals and communities. Section 3 draws general inferences from the literature, Section 4 discusses noise metrics and dosage-effect relationships, and Section 5 identifies recommended research areas. Two Appendices review and summarize the technical literature. Additional appendices provide detailed study designs for recommended research projects.

1.2 Heavy lift rotorcraft designs under consideration

Johnson *et al.* (2005) describe heavy lift rotorcraft designs under consideration for development as large, runway-independent civil passenger transports for use in city-center to city-center markets. Three conceptual designs are reproduced in Figure 1 through Figure 3 of this report for aircraft with gross takeoff weights as great as 130,000 pounds. All three designs are intended to carry similar numbers of passengers to those accommodated by some models of Boeing 737 fixed wing jet transports.

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[1] The term "infrasonic" is used in this report to characterize acoustic energy at frequencies below 20 Hz, while the term "low-frequency" is used both generically, and to characterize energy at frequencies two or three octaves higher. Many sounds, including tiltrotor noise emissions, contain both infrasonic and low-frequency energy.

[2] The term "tiltrotor" in this report refers both to the aircraft design seen in Figure 1, and also more broadly to variants of this design.

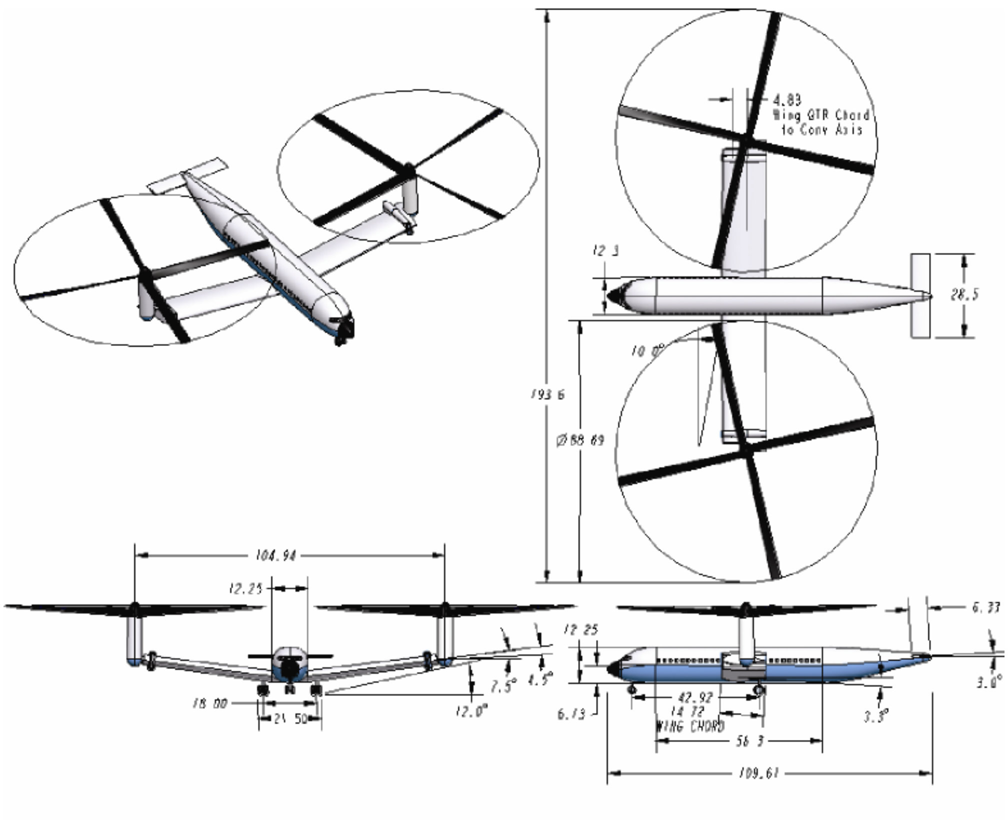

Figure 1: Three-view of large civil tilt rotor [LCTR] (Figure 6 of Johnson *et al.,* 2005)

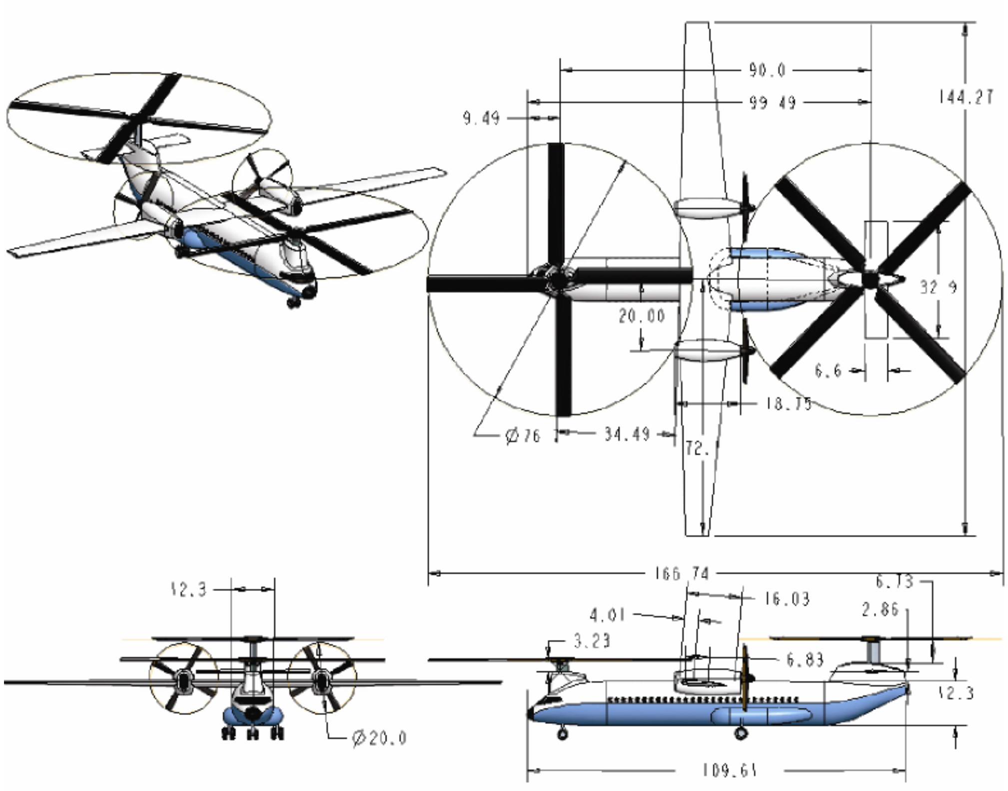

Figure 2: Three-view of large civil tandem compound [LCTC] (Figure 7 of Johnson *et al.,* 2005).

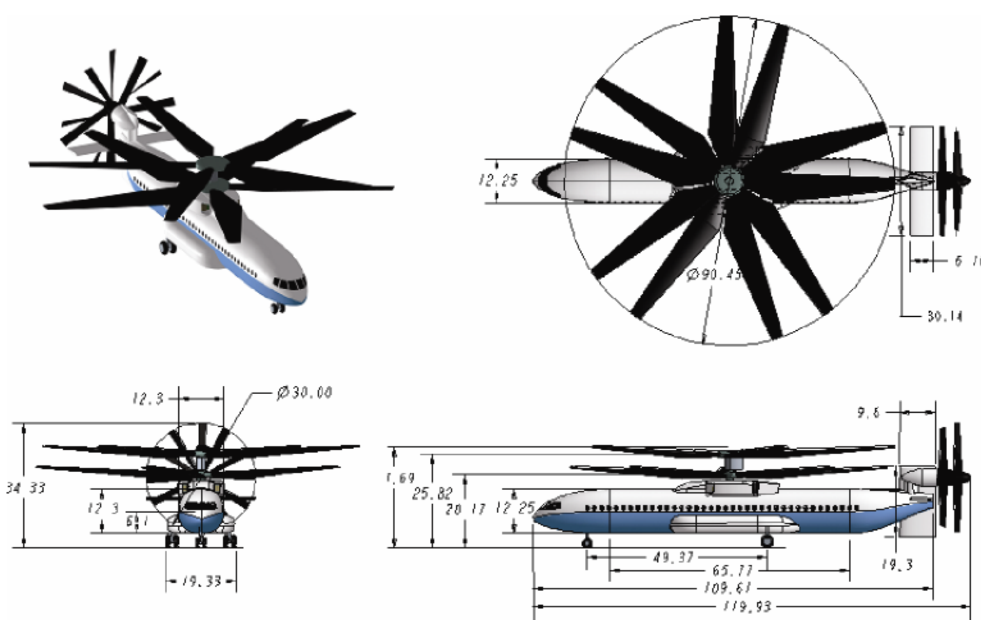

Figure 3: Three-view of large advancing blade concept [LABC] (figure 8 of Johnson *et al.*, 2005).

1.3 Expected tiltrotor low-frequency noise emissions

Johnson *et al*. (2005) estimate effective perceived noise level (EPNL) values of large tiltrotor designs, but not their low-frequency one-third octave band noise levels. These low-frequency noise levels are estimated in the following subsections from first principles, and then adjusted subsequently by scaling trends derived from prior acoustic measurements (Conner, 1994) of a smaller tiltrotor aircraft of similar geometry.

1.3.1 Initial estimation of low-frequency tiltrotor noise levels

Figure 4 summarizes simplifying assumptions made to obtain preliminary estimates of noise levels of a large civil tiltrotor. These assumptions apply to noise produced under steady thrust conditions, and do not take into consideration spectral distortions caused by ground reflections, nor harmonics created during passage of the rotor downwash stream back through the rotor disk.

Figure 5 shows loading and thickness noise estimates for cockpit and passenger cabin positions (assuming no fuselage transmission loss), using the Ffwocs-Williams Hawkings equation (Farassat Formulation 1 for thickness and loading noise, linear terms only) and assuming compact chord and a spanwise triangular loading. Figure 6 shows sound level profiles along lines parallel to the fuselage axis, while Figure 7 and Figure 8 show community noise contours at/near ground level, and at an altitude of 400 feet, respectively. For flight at this altitude, it has been assumed that the noise levels in hover are also representative of those in slow forward flight. While this is not strictly true, it is a reasonable approximation at least for low-frequency harmonic noise.

1.3.2 Results of initial calculations

Peak-to-peak noise levels at the rotor fundamental frequency outside the cockpit approach 125 dB, while those in the cabin are about 10 dB greater. Low-frequency noise levels on the ground plane (ignoring reflections) in the immediate vicinity of the rotorcraft exceed 130 dB in places.

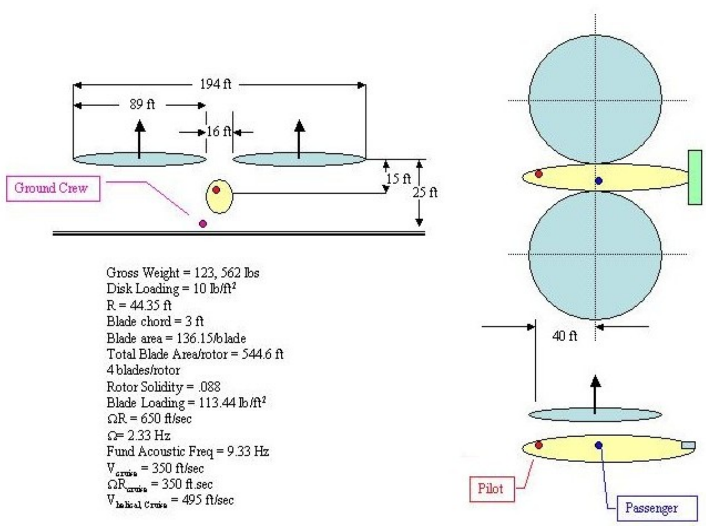

Figure 4: Illustration of assumptions in estimating low-frequency noise levels of large civil tiltrotor.

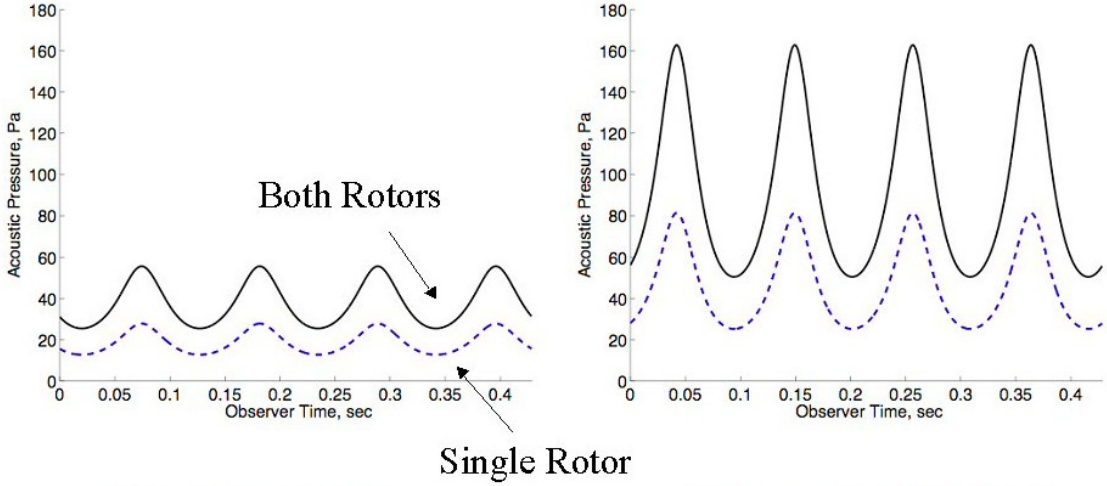

Figure 5: Predicted rotor noise levels of a large civil tiltrotor aircraft outside the fuselage: cockpit (left, peak-peak = 124 dB) and cabin (right, peak-peak = 135 dB).

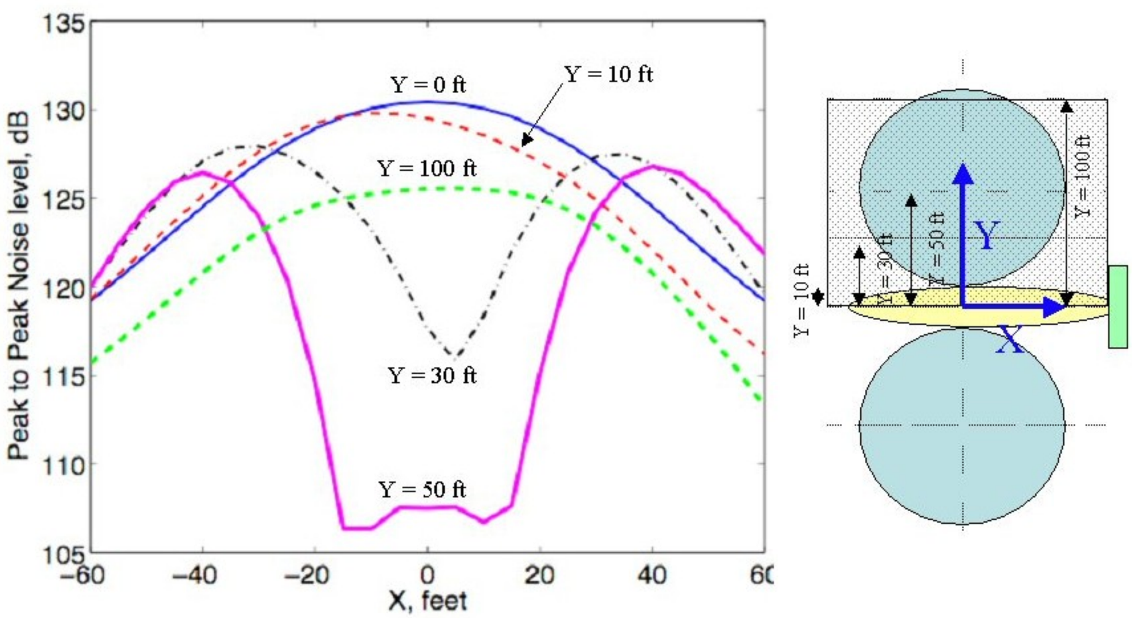

Figure 6: Predicted ground level noise levels of a large civil tiltrotor.

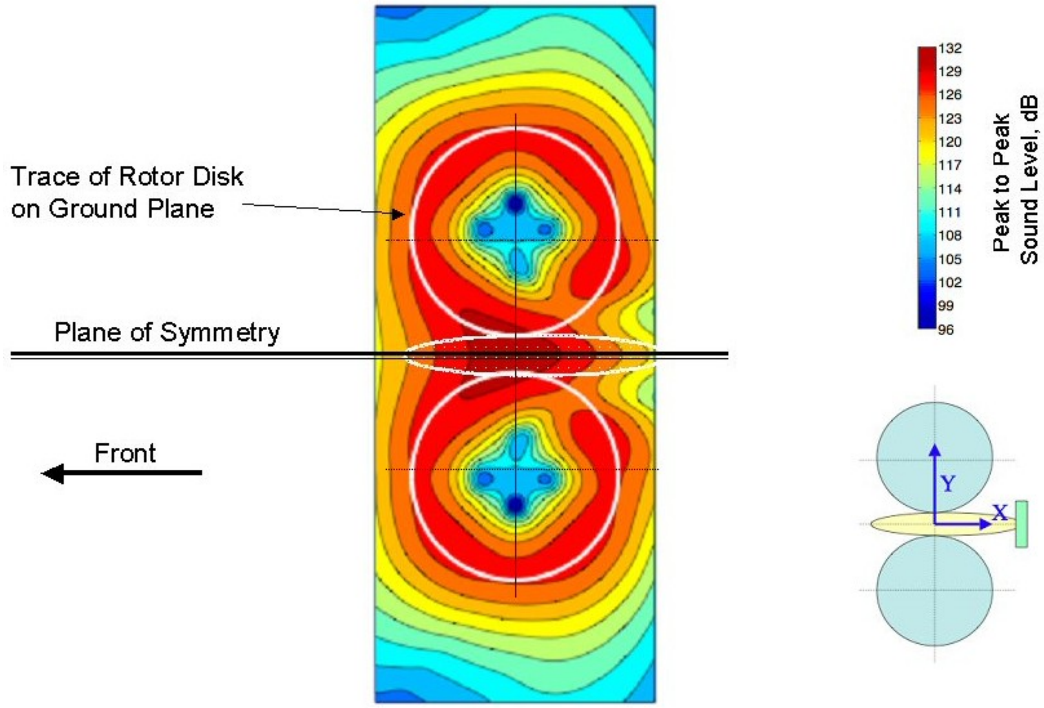

Figure 7: Predicted noise levels for large civil tiltrotor operating on / near ground.

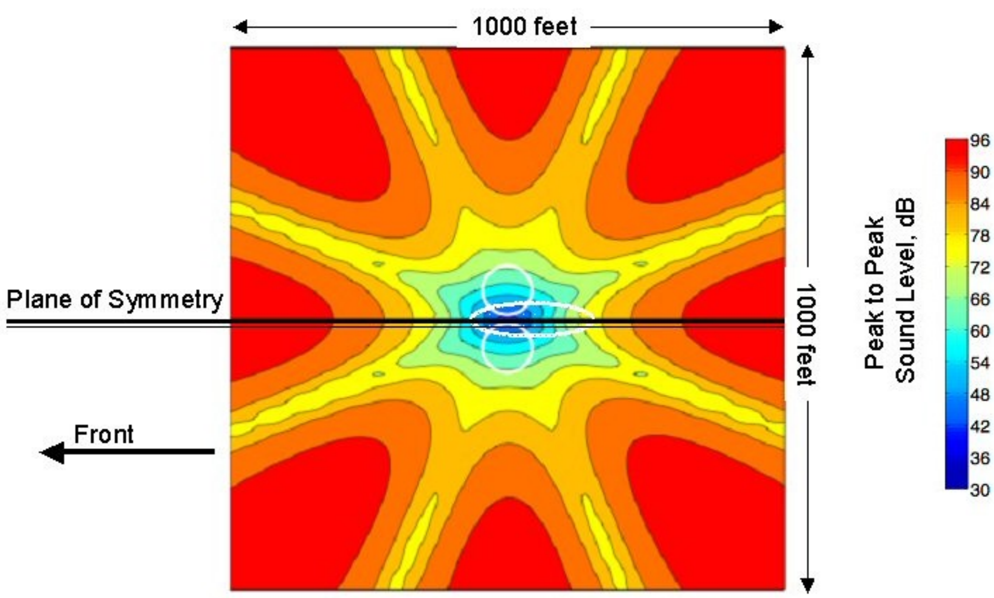

Figure 8: Predicted noise levels for a large civil tiltrotor hovering or in slow forward flight at 400 feet altitude.

1.3.3 Empirical adjustments to initial estimates

Consideration must also be given to effects other than steady thrust, torque, and thickness of the two rotors that can affect noise levels at some measurement positions at low frequencies. The local flow field around each rotor can be influenced by the presence of the wings, fuselage, and ground proximity. These considerations alter the low-frequency loading on the rotor blades, which in turn alter the higher harmonics of the low-frequency acoustics of the vehicle. In particular, a "fountain flow-field" develops near hover that passes up through the two rotors, significantly distorting the rotor's downwash (see Figure 9). Because the blades on both rotors turn toward the rear of the aircraft as they pass over this fountain flow field, the fountain flow field causes higher levels of low-frequency harmonic noise to be radiated toward the rear of the vehicle.

A physics-based, first principles analysis that can estimate this low-frequency harmonic noise is not currently available. However, measurements are available of noise created by a smaller, but geometrically similar tiltrotor aircraft (the NASA/Army/Bell XV-15 aircraft) that experiences these same effects. When the noise radiation is recast in a non-dimensional format, the full-scale XV-15 noise measurements match the noise at the fundamental frequency (blade passage frequency) and the overall SPL trends reasonably well. As expected, the predictions do not capture the higher harmonics of the low-frequency noise above the blade passage frequency. Since the noise level at the fundamental blade passage frequency is not significantly altered, and the overall physics of the fountain effect remain similar between the two vehicles, these higher-harmonic loading effects can be estimated by scaling the measurements of the noise emissions of the smaller XV-15 tiltrotor aircraft.

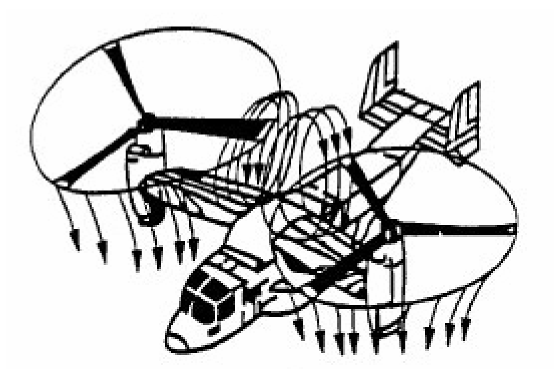

Figure 9: Depiction of fountain flow field recirculation and wake/flow patterns for tiltrotor aircraft in near-ground hover (from McVeigh, Grauer and Paisley, 1988).

Conner (1994) measured XV-15 noise emissions in hovering flight over a range of directivity angles, and corrected the measurements to selected positions on an acoustic sphere as shown in Figure 10. It is clear from the figure that low-frequency harmonic noise drops off much more slowly toward the rear of the aircraft.

The directional trends in fall-off rates of harmonics observed in the XV-15 were subsequently scaled to estimate noise levels from a larger tiltrotor aircraft at similar directivity angles. This approach is not strictly rigorous, and requires a number of assumptions. Low-frequency noise does not follow a 1/R decay law in the near field, and ground reflection and

shielding effects from the aircraft can also affect noise levels. Nevertheless, correcting the data for gross aerodynamic effects is preferable to neglecting these large effects entirely.

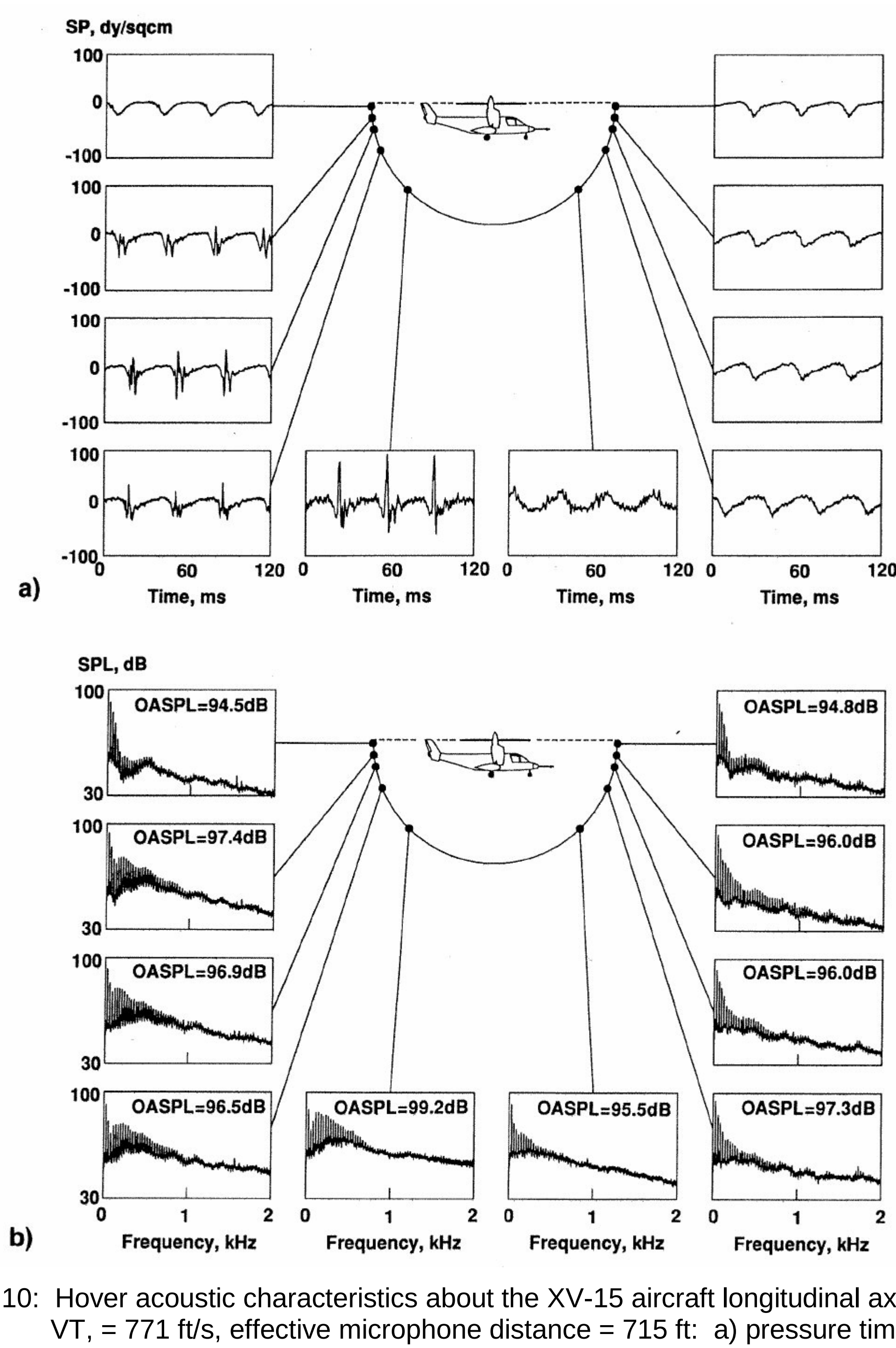

Figure 10: Hover acoustic characteristics about the XV-15 aircraft longitudinal axis; VT, = 771 ft/s, effective microphone distance = 715 ft: a) pressure time histories and b) narrow-band spectra (from Connor, 1994 Figure 8).

1.3.4 Estimated low-frequency exterior sound levels in near-ground hover

Acoustic theory without the fountain flow effects (Figure 6) shows that low-frequency noise levels become large between the two rotors, and reach a maximum at the x = 0 position. These theoretical levels decrease at both the forward and aft positions along the centerline of the aircraft. For a forward position on the ground near the cockpit, the scaled levels of low-frequency harmonics of the large tiltrotor aircraft fall off rapidly with harmonic number (frequency), as shown in Figure 11. This figure shows the rms spectrum level of blade passage fundamental frequency (9.33 Hz) and the rich harmonic structure. Figure 12 replots the data of Figure 11 as one-third octave band rms sound pressure levels.[3]

For crewmembers working at the mid position (between the two rotors) of the aircraft, the harmonic sound levels do not decay as rapidly as shown in Figure 13, due to the effect of the fountain flow. At this position, the fountain effect increases the higher harmonic noise levels in directions aft of the aircraft. Figure 14 replots the data of Figure 13 as one-third octave band sound pressure levels.

This same effect is seen at the rear of the aircraft, where the fountain effect again causes large increases in the higher harmonics of the low-frequency sound levels. This effect is shown in Figure 15. Figure 16 replots the data of Figure 15 as one-third octave band sound pressure levels.

1.3.5 Estimated low-frequency interior sound levels in near-ground hover

Because measurements of aircraft interior levels in the XV-15 (Shank, 1991) are expressed as A-weighted sound pressure levels that are insensitive to low-frequency noise levels, they provide little guidance for estimating the insertion loss of low-frequency harmonic noise through the fuselage skin. In hover, noise levels near the front of the cabin are lowest, while those at farther aft positions increase in A-weighted sound pressure level by as much as 12 dB. The increase is due to the fountain flow effect that dominates noise levels toward the aft of the aircraft.

Shielding and soundproofing effects are minimal throughout the low-frequency range of the harmonic noise of the large tiltrotor aircraft. The predicted low-frequency noise levels in the cockpit (X=40 ft), and two cabin positions (x = 0 ft and x = -40 ft) are therefore estimated simply by subtracting 3 dB from the exterior levels shown in Figure 11, Figure 13 and Figure 15. The slight changes in geometry due to the different elevations of the observer locations and people in the cabin and cockpit do not affect the estimated levels.

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[3] Note that in this and subsequent plots, the fundamental and the first three harmonics do not differ in level from the discrete frequency plot, because only one harmonic occupies each one-third octave band. Two or more harmonics fall within these constant percentage bandwidths at higher frequencies.

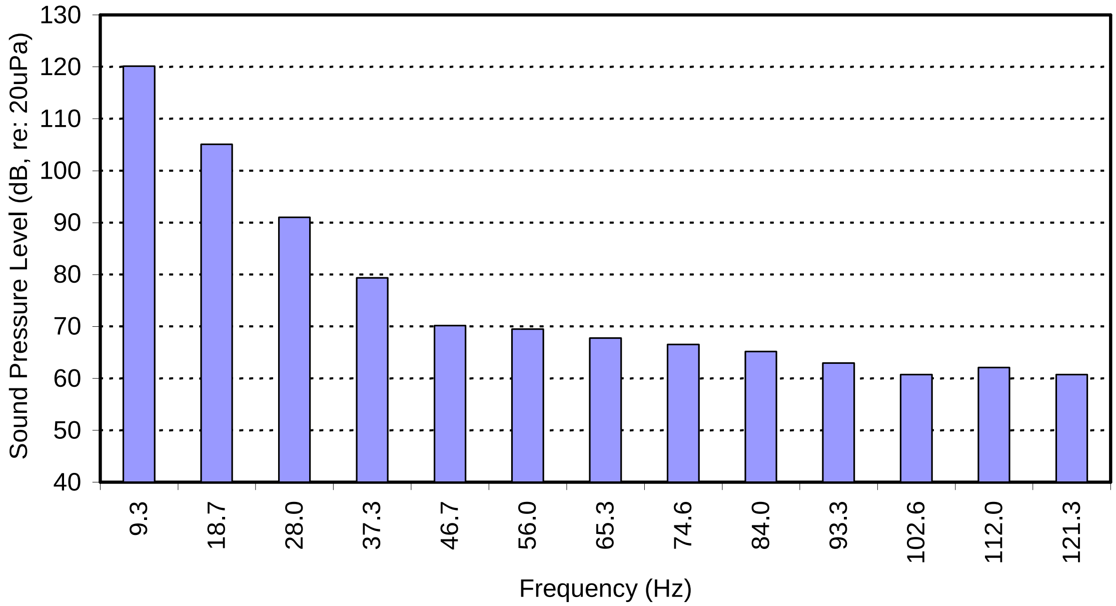

Figure 11: Estimated low-frequency harmonic rms sound levels for a ground crew member near the forward center-line position (X = 40 feet)

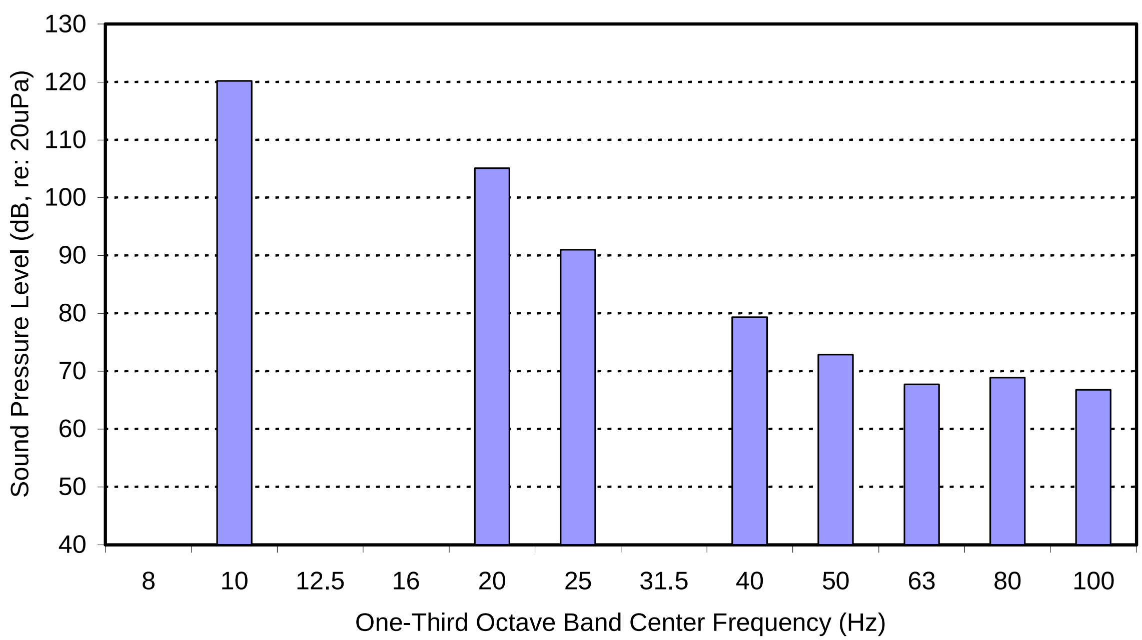

Figure 12: Estimated low-frequency 1/3-octave band rms sound levels for a ground crew member near the forward center-line position (X = 40 feet)

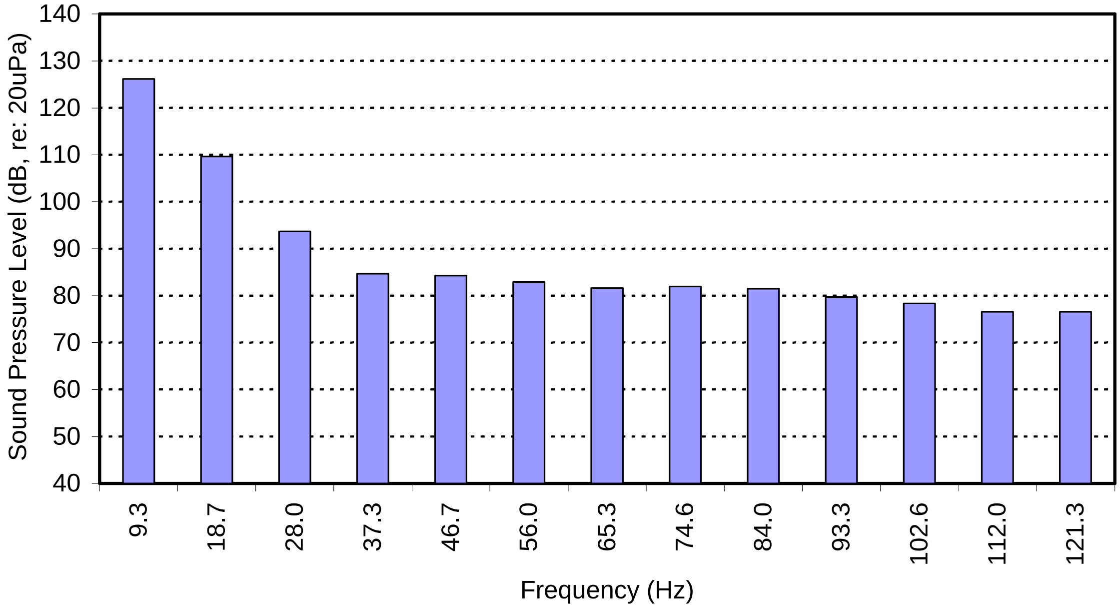

Figure 13: Estimated low-frequency harmonic rms sound levels for a ground crew member at the mid centerline position (X = 0 feet)

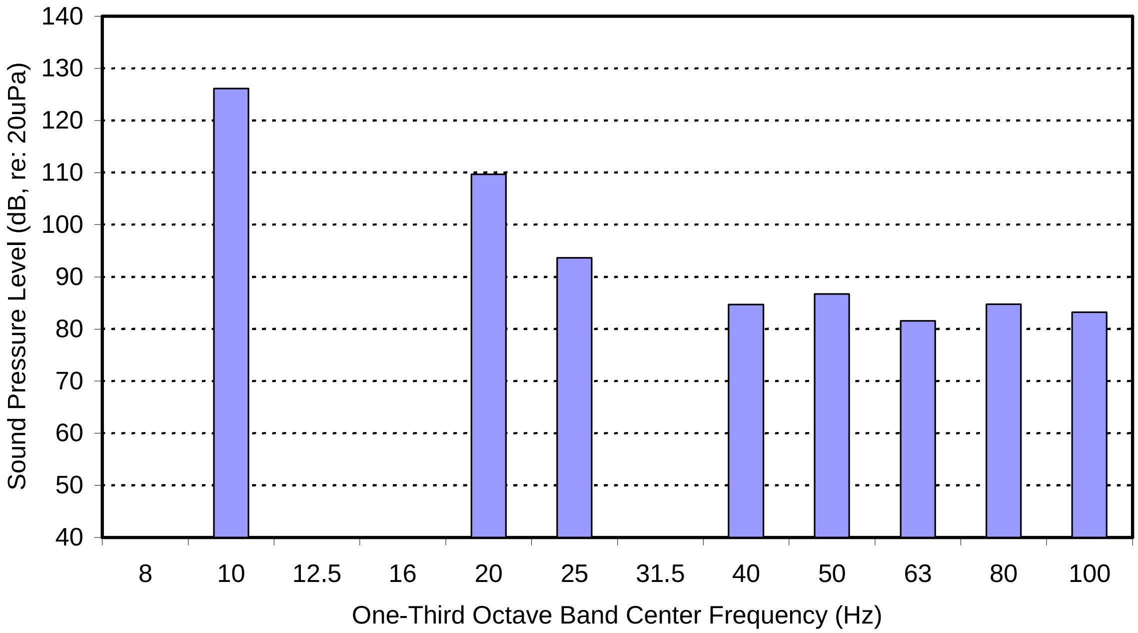

Figure 14: Estimated low-frequency 1/3-octave band rms sound levels for a ground crew member at the mid centerline position (X = 0 feet)

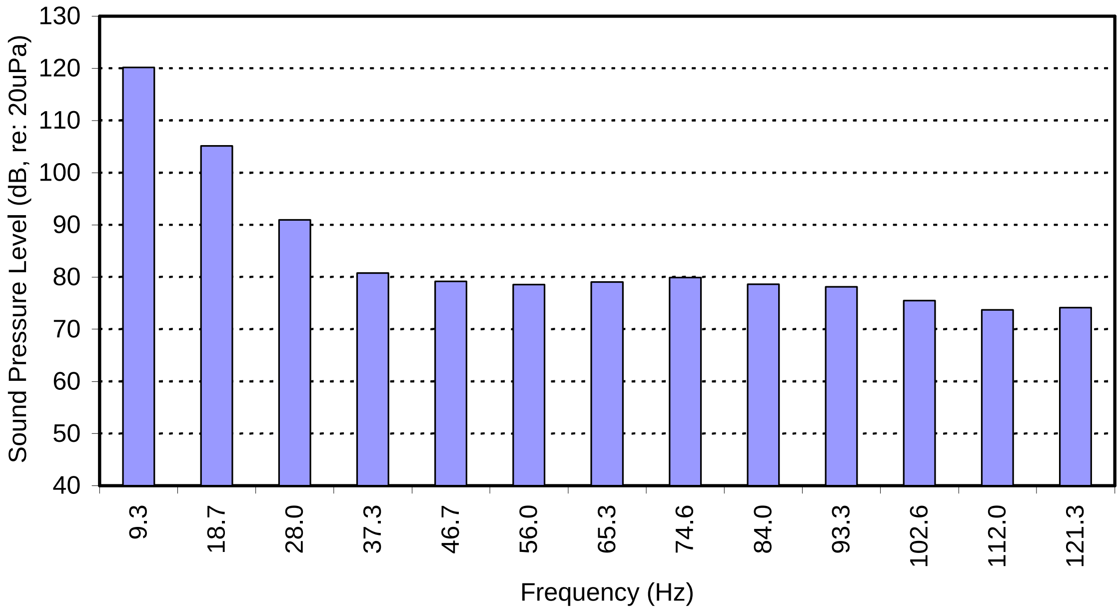

Figure 15: Estimated low-frequency harmonic rms sound levels for a ground crew member at the aft centerline position (X = -40 feet)

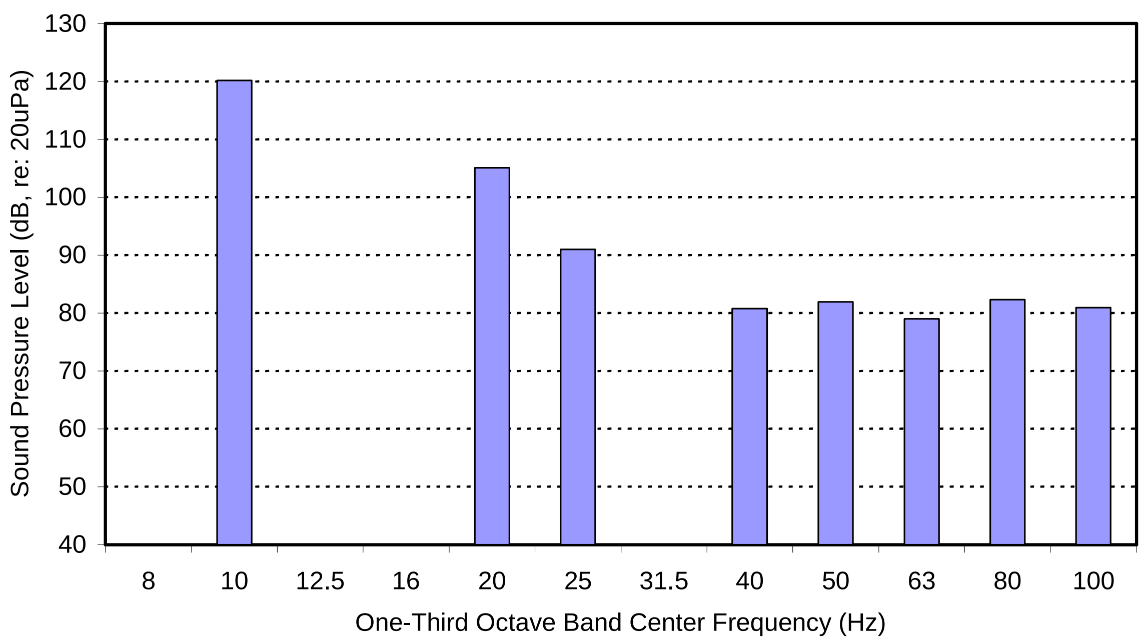

Figure 16: Estimated low-frequency 1/3-octave band rms sound levels for a ground crew member at the aft centerline position (X = -40 feet)

1.3.6 Estimated far-field low-frequency sound levels in helicopter configuration

During landing and takeoff at slow forward speeds, most of the weight of a tiltrotor is supported by the rotors, which are turning at their maximum tip speed (650 ft/sec). The external noise of a large tiltrotor aircraft is therefore quite high when the aircraft is operating in helicopter configuration in the vicinity of landing pads. Operation at 500 ft AGL is taken as representative of flight in this configuration.

The fundamental and harmonic sound level radiation from the large tiltrotor aircraft at two positions along the flight path is shown in Figure 17 and Figure 19. These estimates incorporate the same corrections to the simple theory that were used for the near-field noise estimates.

A position in front and 30 degrees down reveals a noticeable fall-off in harmonic noise (Figure 17). The overall sound pressure level is dominated by the fundamental blade passage frequency of 9.33 Hz. Figure 18 replots the data of Figure 17 as one-third octave band sound pressure levels.

The noise radiation aft of the tiltrotor is shown in Figure 19, in which the slower harmonic fall off rate is once again evident. This slower harmonic noise fall-off rate diminishes as the tiltrotor gains forward speed. As such, these levels should be viewed as an upper bound for a tiltrotor operating in the terminal area. Figure 20 replots the data of Figure 19 as one-third octave band sound pressure levels.

1.3.7 Estimated low-frequency noise levels in cockpit and cabin in slow forward flight

Prior measurements of tiltrotor noise provide little guidance for scaling low-frequency harmonic noise levels in cruising flight. Shank's (1991) A-weighted sound pressure level measurements do, however, indicate some trends for the XV-15 aircraft, which probably apply to a large tiltrotor aircraft as well. The A-weighted sound pressure levels in the cockpit and forward cabin of the XV-15 aircraft in cruising flight (in the aircraft configuration) are about 11 dB lower than in aft cabin positions. The difference is probably due to skin friction noise that increases with airspeed, but is little influenced by low- frequency harmonic noise levels.

Shank's (1991) A-weighted sound pressure level measurements also indicate that the low-frequency harmonic noise in cruise, measured near the cockpit position, is about 6 dB lower than measured levels with respect to those when the aircraft is operated in the aircraft mode at zero forward airspeed. The lower levels in the cruise configuration are probably related to the lower thrust levels that suffice in cruising flight. A surprising finding of Shank (1991) is that the overall A-weighted sound pressure levels for the XV-15 in the aircraft mode in cruise and for the XV-15 in the hover configuration in hover are similar at mid-harmonic frequencies. These higher sound levels in hover are due to the effect of the fountain flow on noise radiation.

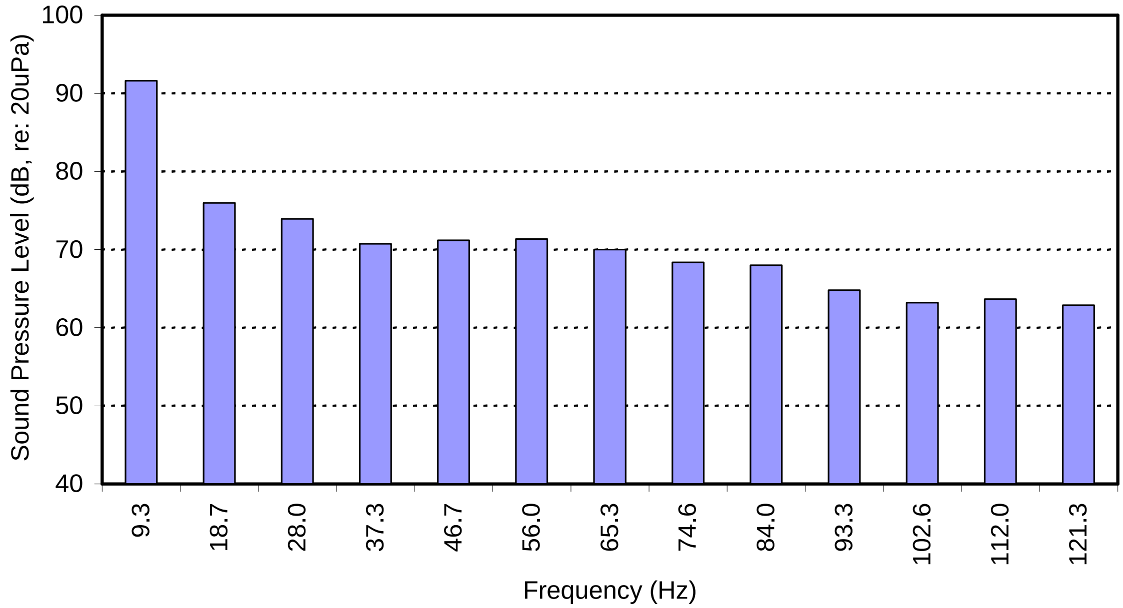

Figure 17: Estimated low-frequency harmonic rms sound levels for a far-field ground observer ahead of the aircraft (X = 866 feet)

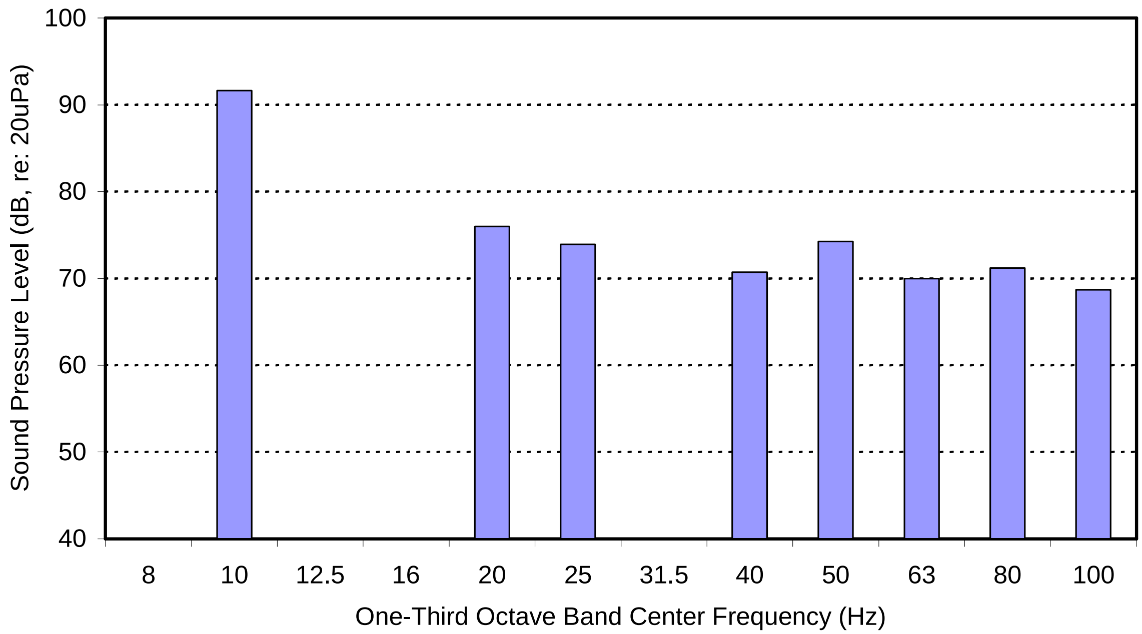

Figure 18: Estimated low-frequency 1/3-octave band rms sound levels for a far-field ground observer ahead of the aircraft (X = 866 feet)

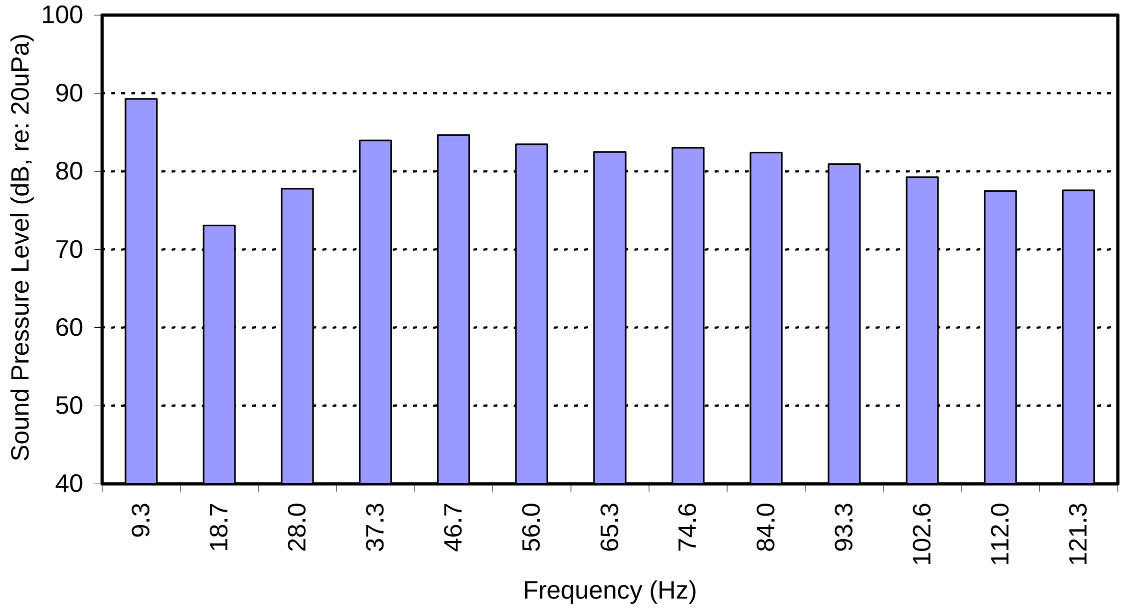

Figure 19: Estimated low-frequency harmonic and 1/3-octave band rms sound levels for a far-field ground observer behind the aircraft (X = -866 feet)

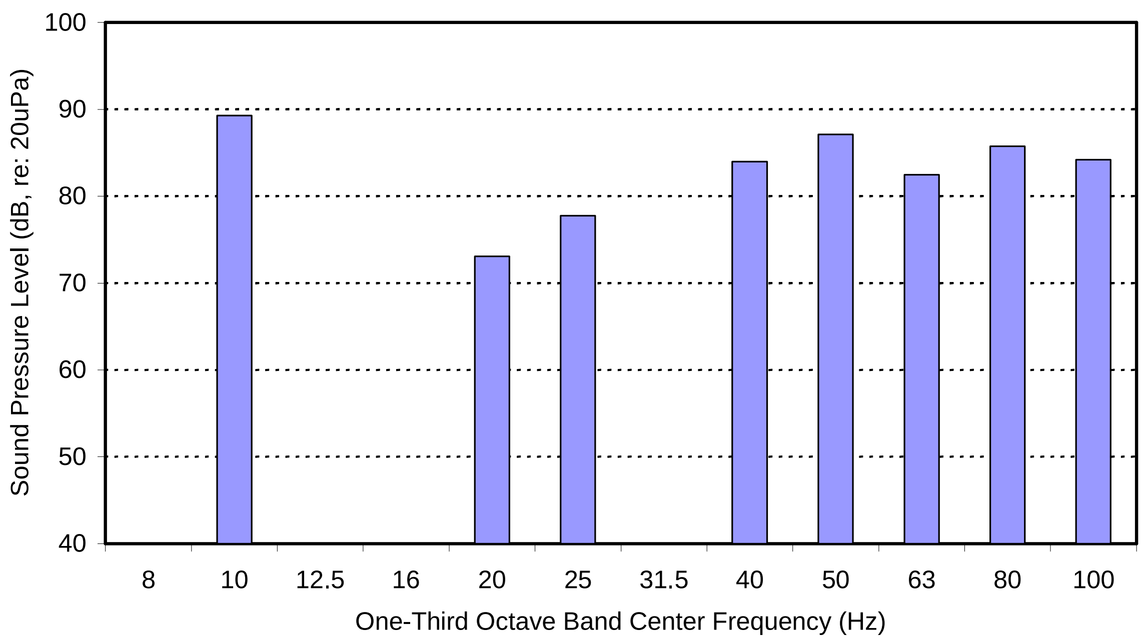

Figure 20: Estimated low-frequency harmonic and 1/3-octave band rms sound levels for a far-field ground observer behind the aircraft (X = -866 feet)

1.3.8 Estimated low-frequency noise levels in cockpit and cabin in high speed cruise

A major design difference between the XV-15 and the large tiltrotor aircraft is the operating tip speed difference between hovering and cruising flight for each vehicle. The XV-15 aircraft reduces rotor tip speed and blade passage frequency by 12%, while the reduction for the large tiltrotor is 46%. The X-15 operates with a cruising tip speed of 668 ft/sec and a helical tip speed of 754 ft/sec. The large tilt rotor tip speed design has a cruising tip speed of 350 ft/sec and a helical tip speed of 495 ft/sec. The very low helical tip speed of the large tiltrotor in cruise will substantially reduce low-frequency harmonic noise both inside and outside the aircraft.

The low tip speed of the rotors of a large tiltrotor in cruising flight, and resulting low helical tip Mach numbers, can be expected to yield low cabin noise levels due to the external flow field and very modest low-frequency harmonic noise in the cabin during cruise, unless the aircraft is designed with very small clearances between the rotors and the fuselage.

1.4 Blade-vortex interaction noise

None of the above estimates addresses the potential for blade-vortex interaction (BVI, or "blade-slap") noise that a tiltrotor can create as the aircraft descends through its own rotor wakes in helicopter configuration. BVI noise typically occurs on descent to a landing in the terminal stages of the approach profile, when the tiltrotor is likely to be close to populated areas. BVI noise typically appears as additional harmonics of higher frequency noise – typically occurring at or above the fifth to sixth harmonic of the rotor fundamental. Strictly speaking, BVI noise is therefore *not* a very-low-frequency noise issue of the sort that is at the core of the current project. Figure 21 compares harmonic levels without BVI noise (in black) against the harmonic levels for typical BVI spectra (in red).

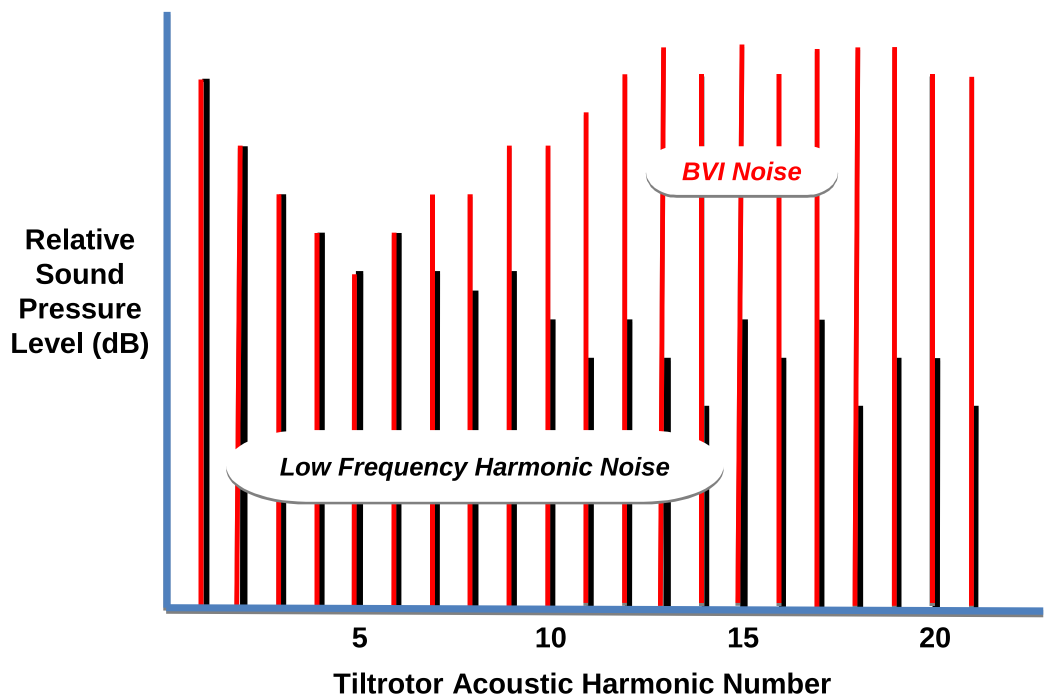

Figure 21: Effect of tiltrotor BVI on harmonic noise levels

An increase in noise level at higher harmonic frequencies can create a great deal of annoyance in its own right. Depending on the flight path flown during an approach to a landing, annoyance due to readily audible BVI noise from a large tiltrotor may be more consequential than annoyance due to the rattle induced by very-low-frequency excitation in residences. Even though BVI is technically not a very-low-frequency noise issue, it will be perceived as a highly annoying impulsive noise repeating at the fundamental frequency of the tiltrotor. Any practical assessment of the potential for adverse environmental impacts of tiltrotor operations will have to include the effects of BVI noise on communities near landing pads.

1.5 Characteristics of exposure to tiltrotor noise

1.5.1 Exposure in the vicinity of tiltrotor landing pads

Large civil tiltrotors designed for runway independent, city-center to city-center transportation are likely to operate not only from dedicated areas at conventional airports, but also from landing pads in downtown areas. In the latter setting, tiltrotors may operate at shorter ranges from surrounding communities than at most airports. This implies that tiltrotor landings and takeoffs will be visually conspicuous in the community. It also suggests that the pulse trains created by its large rotors will be highly distinctive as unique noise events within the more generally continuous urban background noise environment (Schomer and Wagner, 1996).

Smaller landing areas used by tiltrotors might serve as few as a dozen operations per day. Even large tiltrotor facilities in densely populated downtown areas are unlikely to attract as many flights as runway-based airports serving metropolitan areas. Unlike aircraft operations at a busy airport, where hundreds of takeoffs and landings may occur a few minutes apart throughout the day, low-frequency noise effects due to tiltrotor operations may not be noticed more than several times a day. Tiltrotor noise effects are thus more likely than those of fixed wing aircraft to be individually memorable.

Airport workers and residents of neighborhoods near tiltrotor landing pads will experience high levels of infrasonic noise on a recurring but intermittent basis throughout the day. Infrasonic sound levels will be highest on the tarmac in the immediate vicinity of the tiltrotor, and also quite high in the cockpit and passenger cabin. Lower, but still potentially problematic sound levels are likely in passenger terminals and nearby neighborhoods.

Because low-frequency noise emissions of tiltrotors in hover and low-speed forward flight will be highly directional in the plane of the rotor disk and directly beneath the aircraft, the duration of each episode of low-frequency noise exposure during takeoffs and (especially) landings may be as great as tens of seconds. Residents of communities exposed to *en route* noise of tiltrotor aircraft transitioning from cruise to helicopter configuration are likely to experience low-frequency noise less frequently and at lower levels than those residing in the immediate vicinity of landing pads, due to geographic dispersion of flight tracks, higher flight speeds, and differences in directionality of noise emissions.

Two distinct noise impacts associated with indoor exposure to low-frequency noise during a tiltrotor landing are annoyance due to rattle, and annoyance due to direct audibility of BVI noise. At distances as great as a kilometer or more from the landing site, the low-frequency emissions of a tiltrotor are likely to be intense enough to induce annoying secondary emissions (rattle) in household paraphernalia, even before the higher harmonics of rotor noise are prominently

noticeable. At shorter ranges, annoyance due to blade slap from a tiltrotor descending through its own wake may predominate. Even though the two phenomena (rattle and audibility of higher rotor harmonics) are caused by acoustic energy in frequency ranges several octaves apart, casual listeners are likely to consider the two effects as merely early and late manifestations of the approach of a tiltrotor.

1.5.2 Onboard exposure to low-frequency noise

Onboard exposure to the highest levels of infrasonic rotor noise will be concentrated during approach, landing, and takeoff, and will thus be experienced by crew and passengers mostly at the beginning and end of a flight. Infrasonic exposure levels during cruise conditions will be strongly influenced by the clearance between the rotor tips and the fuselage. If the rotor tips pass very close to the fuselage skin, periodic low-frequency variation ("throbbing") induced by aerodynamic pressure pulses may produce noticeable and annoying modulation of broadband noise in the cabin at rotor passage rates.

1.5.3 Exposure of ground observers during cruising flight

Residential and outdoor recreational areas overflown by tiltrotors in cruise configuration are unlikely to be exposed to high levels of infrasound, due to differences from helicopter configuration in rotor orientation and blade passage rates.[4] The exterior A-weighted sound pressure level radiated by the XV-15 aircraft in cruise is 11 dB lower than in its helicopter configuration. (Edwards, 1990). This reduction in level during cruise makes the XV-15 a very quiet aircraft that has been nearly inaudible in high altitude cruise. The large tiltrotor design, although much heavier than the XV-15, has an even greater reduction in rotor operating tip speed and helical tip speed in cruise. The net effect should be a substantial reduction in radiated sound levels of a large tiltrotor compared with the XV-15 sound levels.

[4] The infrasonic and low-frequency noise emissions of a large civil tiltrotor will differ appreciably between hovering/slow forward flight and cruise configurations (Johnson, Yamauchi and Watts, 2005). Rotor tip speeds in helicopter mode may approach Mach .85 (or higher), but will probably be lower than Mach 0.5 in cruise configuration.

2. NATURE OF TECHNICAL LITERATURE

This section is an overview of the literature on low-frequency noise and vibration effects on people and structures, and of some of its limitations for present purposes. Appendix A reviews individual publications, sponsored technical reports, secondary analyses, and summary publications.

2.1 Chronology of infrasound research

Although systematic investigations of the audibility of infrasound can be traced to the pre-vacuum tube era (*cf*. Vance, 1914), modern analyses of auditory sensitivity to very low-frequency sound began two decades later with the pioneering research of von Bekesy (1936), Brecher (1934), and Wever and Bray (1936). Practical interest in the effects of intense infrasound was spurred by the introduction of jet engines in military and civil aviation after World War II, as described in the seminal 1953 "BENOX Report". This report, along with concerns about potential effects of extremely high noise levels produced at low frequencies by manned rocket launches, led to construction of specialized laboratory facilities and multiple studies at the Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base and at NASA Langley Research Center.

Most of the experimental studies conducted in the United States on the effects of intense infrasound on individuals were completed by the 1970s. Interest in Japan, northern Europe and elsewhere in low-frequency noise effects and complaints peaked a decade or two later, although modest numbers of additional studies of the audibility and annoyance of low-frequency noise have been conducted since.[5] The time course of architectural acoustic interest in low-frequency noise effects at lower sound pressure levels, such as those created by air handling systems, generally postdates that in aviation applications (*cf*. Blazier, 1981; Beranek, 1989).

Much of the post-1960s low-frequency research concerns the effects of specialized noise sources, including studies of the hearing damage risk and annoyance of impulsive sources (such as airbags, artillery, blasting, helicopter blade slap, and sonic booms); single-event and non-continuous sources (such as SST engine noise, aircraft engine run-up and ground operations, ground- and structureborne rail vibration and noise); and longer duration sources (such as heavy rotating and reciprocating equipment, industrial-scale combustion facilities, and wind turbines). A recent National Institute of Environmental Health Sciences (NIEHS, 2001) literature search found more than 700 references to infrasound in a dozen biomedical databases, of which more than 150 dealt with environmental health-related matters.

An extensive gray literature of semi-technical accounts of infrasonic effects flourishes on the Internet and elsewhere, ranging from annual reports of research institutes and conference

[5] The numbers and chronology of published, English-language case studies of low-frequency noise complaints and effects suggest a strong social component to low-frequency noise complaints in the late 1970s and early 1980s, particularly in Japan. Similar social trends - at least among researchers - seem to have reached Scandinavia and elsewhere in northern Europe and Australia within a few years.

proceedings, through technical notes, working papers, dissertations and student projects, to popular press reports about putative effects of infrasound. The latter often verge on fringe science, and are replete with accounts of infrasonic weaponry, dire health threats, long range animal communication, earthquake precursors, atmospheric disturbances, structural damage, and the like.

2.2 Relevance and limitations of literature for present purposes

The literature on low-frequency noise and vibration effects includes not only unreliable accounts such as those noted above, but also many reasonable technical investigations that are of only passing interest for present purposes. Because many of these latter reports are essentially irrelevant to assessing onboard and community effects of infrasonic emissions of tiltrotor aircraft, the literature review in Appendix A excludes many articles whose findings are only tangentially related to assessment of tiltrotor noise impacts.

Examples of omitted studies include some analyses of structural response to noise-induced vibration[6], vibration-induced structural damage, human response to groundborne and structureborne vibration, studies of intense noise effects on infra-human species, and so forth. Thus, studies of effects of infrasound on animals (*e.g.*, Cook, Sherry, Brown, and Jauchem, 2001; Parker, Tubbs, Ritz, and Wood, 1976), and effects of broadband noise on performance (*e.g.*, Harris, 1968; Harris, 1972), while of general interest, are not reviewed unless they are specifically relevant to assessment of low-frequency tiltrotor noise impacts.

As described below, many constraints of laboratory and field studies of infrasonic and low-frequency noise and vibration limit their relevance to tiltrotor applications. Descriptions of sound level measurements in many studies are incomplete, particularly in specifying whether reported amplitudes represent root mean square (rms) or peak-to-peak (p-p) values. For sine waves, rms and p-p measurements differ by only 3 dB. For random noise, this difference is about 13 dB, while for impulses the difference between rms and p-p values can approach 20 dB. Measurement bandwidths are not always specified in reporting narrow band (one-third octave band or narrower) sound levels, further complicating comparisons of results. When amplitude and bandwidth specifications are reported by investigators, they are stated as found.

2.3 Overview of laboratory studies

For reasons discussed at length by von Bekesy (1960, pp. 60-69), and by von Gierke and Nixon (1976, pp. 119 *et seq.*), specialized and sometimes costly facilities are required to produce high levels of well-controlled infrasound in the laboratory. Such facilities include electrodynamic, hydraulic, and pneumatic variants on pistonphones, manometers, earcup/loudspeakers, and whole-body pressure chambers. Modern understandings of informed consent and other ethical considerations render a revival of interest in basic studies of adverse effects of very high infrasonic levels unlikely.

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[6] Noise-induced rattle (of light architectural elements such as windows and wall hangings) and vibration are closely related to one another in residences, but rattle is a more common source of aircraft noise complaints than vibration *per se*, and is less affected by idiosyncrasies of building construction. See Section 4.1.2 for further discussion of this issue.

Figure 22 and Figure 23 illustrate 1960s-era, large-scale infrasonic laboratory facilities, both of which have been demolished. Figure 24 is a plan view of a modern facility described by Inukai, Nakamura and Taya (2008). Figure 25 is a photograph of a sonic boom simulator at NASA Langley Research Center.

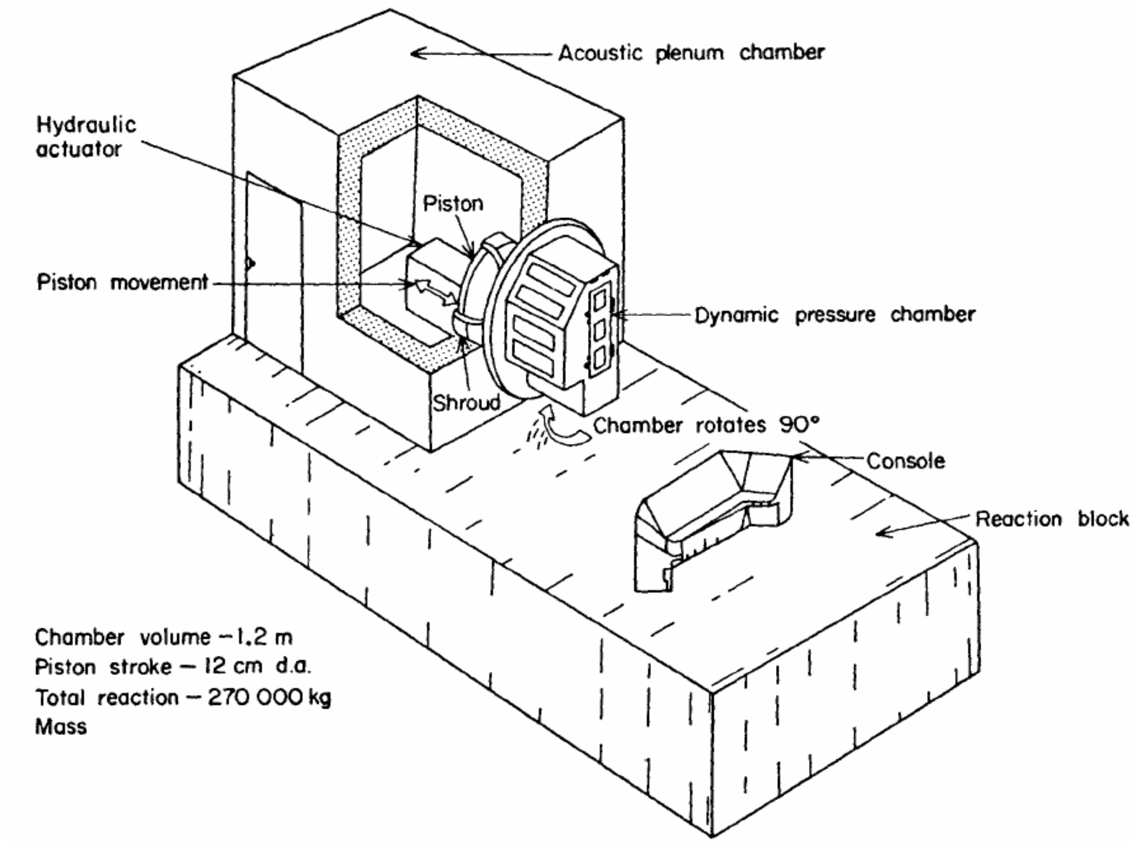

Figure 22: U.S. Air Force infrasonic test chamber at Wright-Patterson Air Force Base (from von Gierke and Nixon, 1976)

Some of the more recent whole-body exposure facilities (*e.g.*, that described by Takahashi *et al.*, 1997, and one designed as a sonic boom simulator at BBN in Canoga Park, CA) use multiple large diameter loudspeakers in a pressurized chamber adjacent to the test space to create a room-size pistonphone. More recently-built facilities for studying very low-frequency effects (*e.g.,* those described by Leatherwood *et al*., 1991, Lydolf and Møller, 1997, and Takahashi *et al.*, 1997) have been unable to produce sound levels at very low frequencies as high as those achievable in the older facilities. Roughly a dozen pressure chambers, ranging from the rudimentary to the elaborate, have been constructed at various times and places for experimentation with high levels of infrasound. Few remain in operation today.

Not all aspects of true infrasound (that is, a propagating longitudinal wave) are readily simulated and controlled. Further, great care is required, both in laboratory and field settings, to avoid distortion products and the confounding of effects of airborne infrasonic exposure with

those of sounds of higher frequencies, and with effects of whole body and touch-sensible vibration.

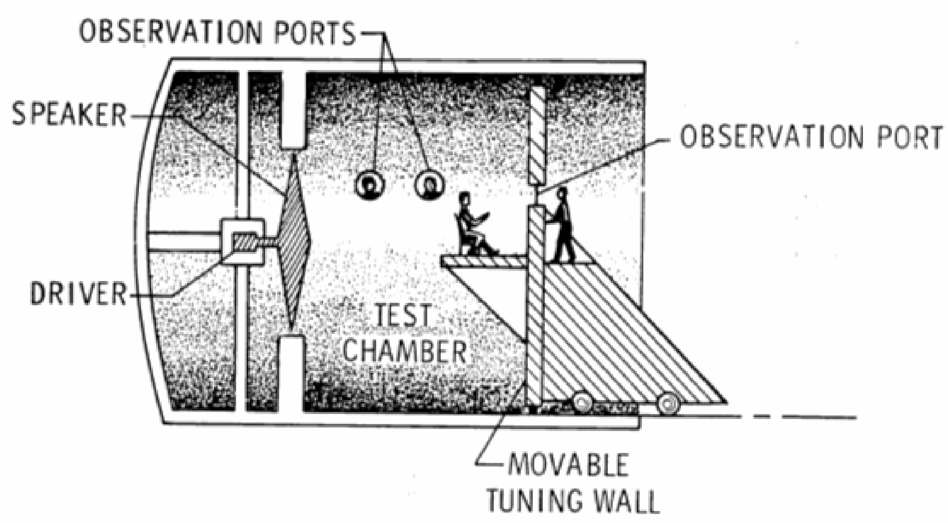

Figure 23: NASA's 1960s-era low-frequency noise facility

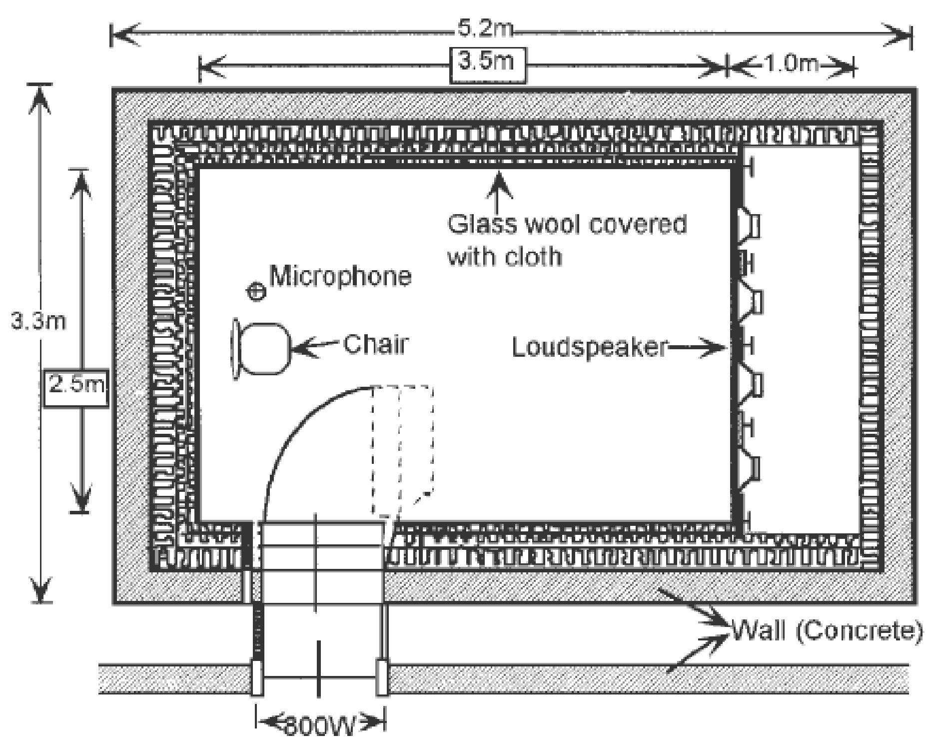

Figure 24: Plan view of a modern low-frequency pressure-field chamber (from Inukai *et al.*, 2000)

Figure 25: Sonic boom simulator at NASA Langley Research Center

Laboratory studies of the annoyance of low-frequency noise, and particularly of impulsive sources, are more numerous than those intended to quantify tolerance limits for infrasonic exposure. Although few laboratory studies of effects of very high levels of infrasound have been conducted since the 1970s, studies of the annoyance of short duration, low-frequency noises such as artillery fire and sonic booms have been among the more common in the last two decades.

Because the circumstances of exposure to impulsive sources of infrasound (sonic booms, blasting, and artillery) differ greatly from those associated with either onboard or community exposure to tiltrotor noise, the findings of such studies are of limited relevance to present interests. Further, as Harris *et al*. (1976) have observed, “Most studies [of adverse effects of infrasound on people] are weak in experimental methodology and in scientific reporting.”[7]

Leventhall (2003) has also alluded to the unreliability of many accounts of infrasonic noise effects, even noting the “mythological” nature of some reports. Leventhall (2003) discusses reports of “false perceptions”; the limitations of correlational analyses of linkages between

[7] Some journals which publish such research are equally susceptible to Harris’s criticisms. For example, the Journal of Low Frequency Noise, Vibration, and Active Control occasionally publishes articles containing meager information and sub-standard (or even no) data analyses. Details of measurements of infrasound such as bandwidths and quantities are not always described, leading to uncertainties in many cases about sound levels associated with reported effects.

annoyance ratings and physical measurements; non-standardized and sometimes non-comparable test stimuli; the care needed in comparing different varieties of response indices and their sensitivity to test conditions; large variability between subjects; the unreliability of differences between A-weighted and C-weighted sound pressure level measurements as a predictor of annoyance; the psychosomatic origin of sensitivity to unidentified low-frequency noises (*e.g.*, various place-specific "Hums"); and so forth.

The quality of individual studies is very uneven. Non-peer reviewed studies, such as conference papers and similar accounts of low-frequency studies, are often vague or even anecdotal, so that a good deal of the literature is inconclusive and generally unhelpful for present purposes. For example, Yuan, Qibai and Shi (2004) conclude that "Different individuals have different responses to infrasound and the change ratio of blood pressure and heart rate are also different"; and "By comparing physiological and psychological effects of infrasound on persons in two different infrasound conditions, we find that there are not obvious differences." Many such studies provide no useful guidance for assessment of impacts of infrasonic noise associated with tiltrotor operations.

2.4 Overview of field studies

Field studies of infrasonic and low-frequency effects of noise are of interest for present purposes to the extent that they may shed light on community response to tiltrotor operations. Few such well-controlled studies have been conducted in residential settings.[8] Most field studies of low-frequency noise and vibration effects have been adventitious (that is, have relied on extant infrasound exposures, whether real or supposed), and often limited to small-scale case studies in uncontrolled industrial and office settings. Firm conclusions and quantitative dosage-effect relationships are few and far between in this literature.

Measurement of low-frequency and infrasonic exposure in field studies is often absent (*cf.* Persson Waye, 2004) or indirect at best, as by inference from differences of 20 dB or more between C-weighted and A-weighted sound pressure levels (*e.g.,* Tesarz *et al*., 1997). Many findings of field studies of low-frequency noise effects are confounded by noise at higher frequencies, while interpretations of field studies of low-frequency vibration effects are generally limited by the inherently location-specific nature of vibration measurements. Other limitations in application of the findings of field studies are imposed by the purely correlational nature of study design (*e.g.*, Green and Dunn, 1968), informal observational intent (Møller and Lydolf, 2008), and frankly speculative nature of authors' interpretations (Manley *et al*., 2002; Persson Waye, 2004).

Fidell (1996) summarizes many of the field studies of community response to high-energy impulsive sounds (most notably, sonic booms and artillery), and synthesizes dosage-effect relationships from them. Studies of low-frequency community noise created by wind turbines

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8 See Pawlaczyk-Łuszczyńska (2006) and Leventhall (2003) for reviews of largely northern European and Japanese low-frequency occupational noise exposure case studies. Some reports of serious physiological symptoms attributed to infrasound in Soviet-era eastern European industrial exposure studies are particularly dubious, due to flawed epidemiological methods. Other published reports of small-scale Scandinavian case studies, whose findings are interpreted by their authors as suggestive of the importance of additional similar research, are also methodologically weak.

(*cf.* Hubbard, 1982; Stephens *et al*., 1982; Kelley, 1987), aircraft (*cf.* Powell and Shepherd, 1989; Schomer and Neathammer, 1985; and Fidell *et al.,* 2002) and industrial sources such as large marine diesel engines (*cf.* Nishiwaki and Mori, 1978) tend to focus on noise-induced building rattle, and on the annoyance of low-frequency tonals. The annoyance of low-frequency rumble induced by structureborne vibration excited by underground and surface rail has also been investigated (*cf.* Öhrström and Skånberg, 1996; Klæboe *et al.*, 2002).

Several field studies of the annoyance of low-frequency runway sideline (thrust reverser) and start-of-takeoff-roll have been completed in recent years (*cf.* Fidell *et al*., 1998; Fidell *et al*., 2002; Hogdon *et al.,* 2007; as well as airport-specific consulting studies at AMS, BOS, BWI, and SFO). The consulting studies (such as those of Sharp, Gurovich and Albee, 2001, and HMMH, 1996 and 1998) focus on local rather than broader research issues, such as "backblast" noise in San Francisco and building vibration in Baltimore.

It is useful to bear in mind several distinct mechanisms of annoyance that have been explored in field studies: the direct annoyance of airborne low-frequency noise *per se;* the annoyance of structureborne vibration induced by airborne (and occasionally by groundborne) low-frequency noise; and the annoyance of secondary acoustic emissions (audible rattle) induced by either airborne or groundborne vibration. In the community settings and likely range of sound levels of current interest, rattle induced by airborne noise coupled to structures is generally the more salient of these mechanisms of annoyance.

3. GENERALIZATIONS SUPPORTED BY LITERATURE REVIEW

The literature reviewed in Appendix A contains only a modest amount of information directly relevant to assessment of the effects of noise emissions of a large civil tiltrotor. This information is not sufficiently extensive, comprehensive or reliable to support a quantitative "balance of the evidence" meta-analysis. It nonetheless supports the general observations made in the following sub-sections.

3.1 Summary of major findings

Three categories of infrasonic and low-frequency noise effects on individuals and communities that have been reported in the technical literature are (1) physiological responses to very high sound levels, (2) attitudinal responses of workers to audible low-frequency sound in industrial and other occupational exposure settings, and (3) community (that is, residential) response to noise-induced rattle, perceptible vibration, and perceived structural damage risk associated with aircraft and other noise sources.

Figure 26 is a graphic summary of information contained in Table 10 of Appendix A. The lower set of data points plots estimates of the threshold of hearing at frequencies below 100 Hz. The upper set of data points plots individual accounts of noxious effects of infrasound and low-frequency noise, including aural pain and limits of voluntary exposure.

The three colored regions in the graphic are intended to distinguish combinations of onboard tiltrotor frequencies and sound pressure levels that should be non-objectionable to passengers and crew (green); that are potentially acceptable in commercial service (yellow); and that are clearly intolerable, even for short periods of time (red). Regions shown in lighter shades of orange approach within 10 dB of levels that laboratory test subjects have been unwilling to voluntarily tolerate. Note that there is far less separation between green and red in the infrasonic range than at frequencies above 10 Hz.

The gradations of saturation in color across regions are intended as a reminder of the inherent imprecision in published findings stemming from small numbers of studies and test subjects, less-than-precise measurements and control of signal presentation conditions, infrequent replication of findings, and sometimes contradictory results.

3.2 Improbability of consequential physiological effects

Levels of voluntarily tolerated acute exposure to infrasound are reasonably well established, and unlikely to be exceeded in cockpit and cabin spaces of a commercially viable, large civil tiltrotor. Most researchers conclude that adverse physiological consequences of short duration exposures to infrasound are of little or no clinical significance, or even of pragmatic concern, except at extremely high levels (*i.e.*, in excess of 140 - 150 dB). Even temporary threshold shifts associated with infrasonic exposures at levels likely to be produced in the cockpit and passenger cabin of large civil tiltrotor are of minor concern.

Intermittent onboard and ground-crew exposures to infrasonic and low-frequency tiltrotor noise are thus unlikely to pose meaningful risks to either auditory or extra-auditory health. Levels of chronic exposure to infrasound that might conceivably be hazardous to health remain unknown, but are probably at least 20 dB greater than hearing thresholds.

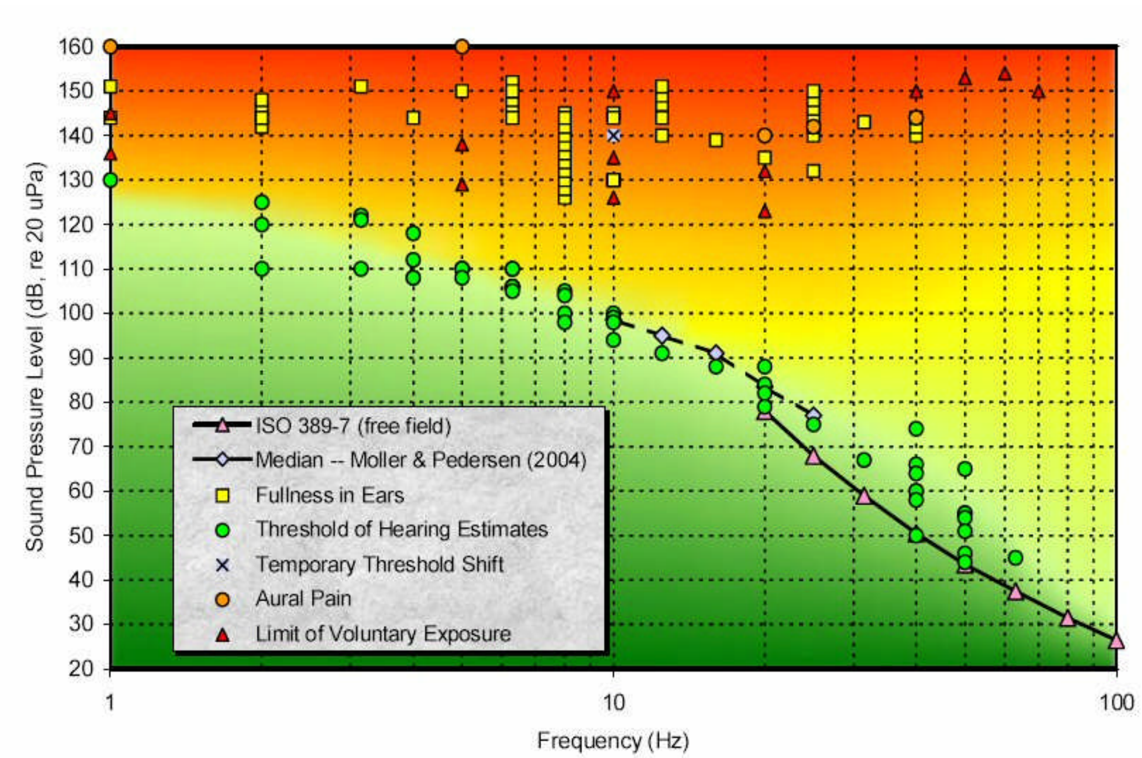

Figure 26: Illustration of regions of non-objectionable (green), potentially acceptable (yellow), and intolerable (red) onboard exposure to low-frequency noise and infrasonic energy

Likewise, tiltrotor operations are unlikely to pose meaningful public health hazards in residential areas near landing pads. A few researchers (*cf.* Berglund *et al.*, 1996) argue in favor of "concerned action" even without clear evidence of adverse health effects at lower level exposures. Such non-evidentiary arguments appear to be based on repeated anecdotal accounts of sub-clinical effects, and are rooted more in philosophical views than in plausible, direct, or rigorous epidemiological findings.

3.3 Likelihood of community annoyance

Low-frequency and infrasonic noise levels that pose no risk of physiological harm may still be unpleasant, uncomfortable, or otherwise unacceptable in commercial transportation, and in residential and outdoor recreational settings. Low-frequency noise and rattling created by tiltrotors are very likely to be noticed indoors in overflown areas near landing pads, and are likely to annoy many residents. (Recall also that BVI noise, although not strictly speaking an infrasonic or a very low-frequency issue, can also be highly annoying, and is likely to be confused in community settings with low-frequency noise effects.)

3.4 Sensitivity of reported effects to small changes in level

It is commonly reported that the range of sound pressure levels separating inaudibility from consequential effects of infrasonic exposure is surprisingly small. The abrupt transition from

green to orange regions in Figure 26 at frequencies below about 10 Hz illustrates this finding. The widely-reported compression of dynamic range over which effects grow from negligible to consequential suggests not only a need for tight tolerances for design guidance concerning the acceptability of the cockpit noise environment and comfort of the passenger cabin, but also the possibility of complaints from heliport neighbors at infrasonic levels not much greater than masked thresholds.[9]

3.5 Inappropriateness of conventional noise metrics for assessing tiltrotor noise impacts

Conventional (A-weighted) metrics of transportation noise are by definition of no utility for present purposes, since the customary family of single event, sound exposure, equivalent level, and cumulative time-weighted average measures are highly *in*sensitive to acoustic energy in the frequency region of interest. The insensitivity of conventional units to infrasonic and low-frequency tiltrotor noise is the lesser part of the problem, however. The greater part of the problem is that even if an expedient set of low-frequency noise metrics were constructed in C-, G-, or other low-frequency weighting units, the near complete lack of empirical or policy-based interpretive criteria would deprive them of usefulness for purposes other than measurement for measurement's sake.

Arbitrary measures of tiltrotor noise levels, such as differences between A- and C-weighted sound pressure levels, are likewise of little utility. Even highly detailed measures of the masked audibility of tiltrotor noise emissions (*e.g.,* bandwidth-corrected signal-to-noise ratios) offer only a partial solution to problems of assessing tilt rotor noise impacts, because the literature offers scant quantitative documentation of the willingness of individuals and communities to tolerate low-frequency noise intrusions, no matter how measured. Indeed, it is not always clear whether community response to low-frequency pulse trains is more appropriately assessed by their direct audibility, or by the secondary emissions that they induce in residences.

Given the episodic nature and relative infrequency of exposure to high levels of rotor noise in communities near downtown tiltrotor landing pads, long-term average exposure measures are unlikely to be useful for quantifying low-frequency tiltrotor noise impacts. Although the time constants of arousal and decay of annoyance associated with familiar transportation noise exposure may be measured on a scale of tens of hours, windows in residences will rattle in real time when tiltrotors occasionally fly nearby.

These observations suggest that single event and centile-based noise metrics may prove more appropriate than long-term cumulative noise metrics for assessing tiltrotor noise effects. One such measure, LFSL, may offer a model for noise metrics appropriate for predicting community response to tiltrotor noise. Note, however, that LFSL was tailored to the range of low-frequency noise emissions of large jet engines that power fixed wing transport aircraft, and that the noise emissions of tiltrotors will produce yet greater levels of narrower-bandwidth, very low-frequency energy than the noise sources for which LFSL was developed. These issues are revisited in greater detail in Section 4 of this report.

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[9] Substantial differences between 1987 and 2003 versions of ISO's low-frequency equal loudness contours complicate interpretations of the magnitude of this compression, however.

3.6 Role of non-acoustic factors in community effects

Non-acoustic ("response bias") factors are often reported to play a large role in community reaction to very low-frequency sounds. Several investigators have been unable to link low-frequency noise complaints to measurable low-frequency noise sources. In some cases, complaints have persisted after sources of low-frequency noise have ceased operation.

A number of British, Japanese, and Scandinavian researchers favor the hypothesis that individuals of unusual sensitivity (a small proportion of the general population) are common among infrasound complainants and low-frequency noise "sufferers". This hypothesis is neither necessary nor sufficient to explain community response to low-frequency and infrasonic noise exposure. Further, research directed at identifying personality or other individual characteristics of low-frequency noise complainants is of little relevance for tiltrotor design-related purposes.

3.7 Paucity of dosage-effect relationships

The literature on low-frequency and infrasonic noise effects contains few dosage-effect relationships derived from field measurements of relationships between exposure and non-auditory effects that are directly useful for present purposes for a variety of reasons:

1) The general goal of most early (that is, military) research on infrasonic effects was to establish maximum acute exposures levels tolerated by individuals familiar with low-frequency noise, not to document effects of chronic exposure on naïve personnel or general residential populations (such as those living in communities near potential tiltrotor operating areas), nor to investigate effects of lesser or longer duration exposure levels.

2) The original research on which quantitative relationships could be based is too sparse (too few simulation facilities, too few test conditions and large-scale studies, non-representative test participants, unreplicated findings, *etc.*) to support synthesis of reliable dosage-response relationships.

3) Adventitious exposure case studies in field settings generally have not isolated, reliably controlled, nor accurately measured infrasonic noise exposure.

4) Later laboratory studies on the acceptability and annoyance of low-frequency noise exposure have produced only indirect estimates and evidence from which dosage-response relationships could be constructed.

5) European standards for residential exposure, and for career-long, occupational exposure to low-frequency and infrasonic noise are commonly based on scant (industrial or occupational case study) evidence, and are not readily generalizable in any event to short duration circumstances of exposure to tiltrotor operational noise.

6) Systematic field investigation of representative, large population residential reactions to transportation noise exposure at very low frequencies (in contrast to small scale case study) are few in number and relatively recently undertaken (*e.g.*, Fidell *et al.*, 1999, 2002). Large scale, well-controlled studies focused solely on quantification of community response to infrasonic transportation noise have yet to be conducted.

The closest approximations to systematic dosage-effect relationships are for the audibility of low-frequency and infrasonic sound levels (as illustrated in Figure 77 on page 131) and for the annoyance of low-frequency, noise-induced rattle (as illustrated in Figure 70 on page 117).

3.8 Cognitive effects and task performance

Few credible reports have been published of meaningful adverse effects of infrasound at levels below 120 dB on cognitive or task performance. Incapacitation due to lethargy, nausea, involuntary nystagmus, headache, or pain in the ears and body cavities is not a realistic concern at inaudible infrasonic levels. Distraction and mild annoyance due to onboard notice of unfamiliar infrasonic auditory sensations could detract from overall ride comfort at somewhat higher levels, and speech modulation could conceivably degrade intelligibility of onboard verbal communication.

4. DOSAGE-EFFECT RELATIONSHIPS AND NOISE METRICS

Task 2.1 of Contract NNLO8AA52C calls for “additional analyses to yield dosage-effect relationships and recommend and justify appropriate metrics” for assessing tiltrotor low-frequency noise metrics. These matters are addressed in the following subsections.

4.1 Criteria for exposure to low-frequency noise

4.1.1 Proposed frequency-weightings for acceptable sound levels

Several frequency-weighting functions have been proposed for quantifying low-frequency sound levels (*cf*. the G1, G2, LSL, and LSPL functions noted by Tokita *et al.*, 1984). These and the more familiar A- and C-weighting functions are summarized in Table 1 and illustrated in Figure 27.

Table 1: Standardized frequency-weighted sound levels

Sound Level Weighting	Source	Description
A	ANSI 1.4-1983 (R2006)	Nominal equal-loudness at low sound levels
B	ANSI 1.4-1983 (R2006)	Nominal equal-loudness at moderate sound levels
C	ANSI 1.4-1983 (R2006)	Nominal equal-loudness at higher sound levels
G	ISO 7196:1995	20 Hz peak, high rolloff either side. No justification for curve shape provided in standard, but presumably noise-induced structural excitation (rattle).
G1	Tokita *et al.* (1984)	20 Hz peak, and eventually adopted as the G curve, above.
G2	Tokita *et al.* (1984)	20 Hz peak very similar to G1, but with less attenuation of the low frequencies than G1.
LSL	Tokita *et al.* (1984)	50 Hz peak with spectral shape very similar to G1.
LSPL	Tokita *et al.* (1984)	Broad, flat response from 2 to 50 Hz, with steep rolloff on either side.

All but one of these functions (LSPL) is characterized by a spectral peak with steep rolloffs on either side. The sharp peaks suggest targeted resonant frequency responses, either structural or physiological. According to Tokita *et al.*, these functions are all meant to address a combination of structural response effects such as rattle, as well as “feelings of oppression and vibration,” presumably in differing proportions for different weighting functions.

Neither Tokita *et al.* (1984) nor Tokita and Nakamura (1981) provide detailed rationales for the shape of each weighting function, but they do argue in the former citation that the LSL curve provides a superior account of subjective response in the absence of rattle. However, a commonly noted resonant frequency for stick-frame residential structures is on the order of 20 Hz, so to the extent that vibration-induced rattle affects annoyance with tiltrotor emissions, weighting functions that peak in this frequency range may be useful in predicting rattle.

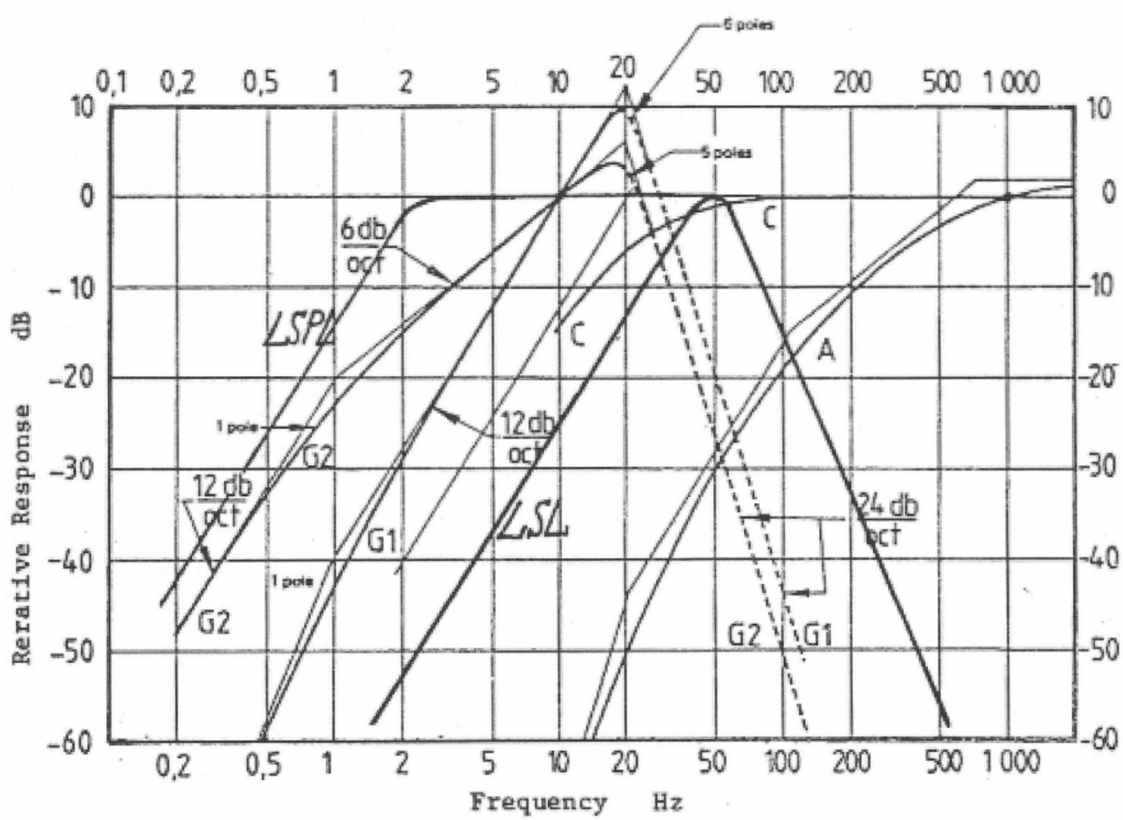


Figure 27: Various low-frequency weighting functions identified in Tokita *et al.*, 1984 (Figure 2).

Absent a rationale for the weighting functions, it is difficult to evaluate how appropriate any may be for present purposes. Even the G1 weighting function identified by Tokita *et al.* (1984), and subsequently standardized as ISO 7196:1995, lacks any descriptive rationale useful for evaluating its applicability to present purposes.

The Danish Environmental Protection Agency (DEPA) issued an information report on low-frequency noise, infrasound and vibrations (Danish Environmental Protection Agency, 1997). The report recommends that indoor noise in dwellings should not exceed a G-weighted sound pressure level of 85 dB for the infrasonic (< 20 Hz) portion of the spectrum, and an A-weighted sound pressure level of not more than 20 dB for low-frequency noise over the broader range of 10-160 Hz. Without more systematic investigation, it is difficult to determine how well a single-number, low-frequency metric can meaningfully describe effects of heavy-lift rotorcraft noise on overflown populations.

The G-weighting frequency function is replotted in Figure 28 along with the familiar A, B, and C-weighting functions. The frequency range of this figure is bounded by 0.1 Hz to 1000 Hz to illustrate the extreme low-frequency behavior of these functions.

The D-weighting frequency function (International Electrotechnical Commission, 1976) is also included in this figure. Although no longer used, the D-weighting function was intended to approximate the frequency weighting incorporated by the perceived noise level (PNL), still used for aircraft noise certification purposes under FAR Part 36. Although the frequency weighting function incorporated in the perceived noise level varies with the sound pressure level in each one-third octave band, the D-weighting function represents the 40 noy contour for moderate to high sound pressure levels in each band.

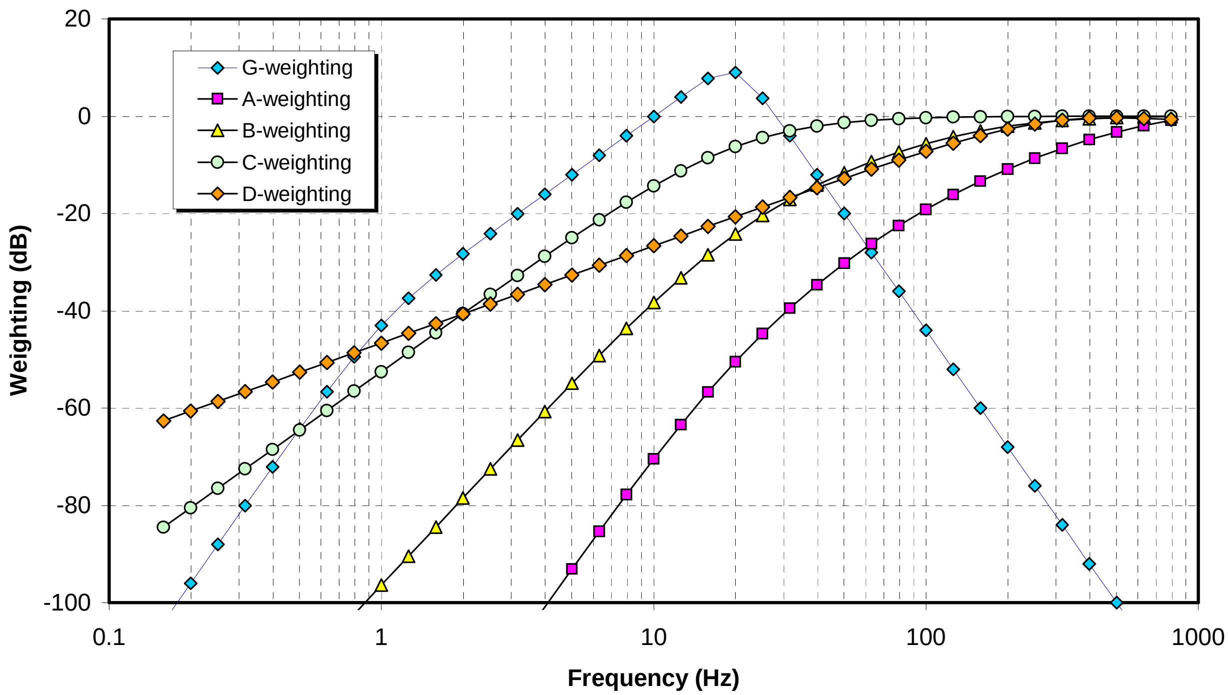


Figure 28: Common frequency weighting functions and the G-weighting of ISO 7196:1995

The curves of Figure 28 are replotted in Figure 29 to focus on the frequency range of current interest. Note that between 1 and 25 Hz, the C-weighting function parallels the G-weighting function, with an average difference on the order of 13 dB. Hence, if the dominant energy in the noise spectrum is below 25 Hz, it is possible that the C-weighted sound pressure level may act as an effective surrogate for the G-weighted sound pressure level. Because correlation is insensitive to constants, strong correlations for both metrics may be found with the incidence of rattle. If considerable energy is present above 25 Hz, the C-weighting function *may* not perform as well as the G-weighting insofar as rattle prediction is concerned. However, Kelly (1987) found that the C-weighted sound pressure level appeared to correlate better than G1, G2, LSPL, LSL, and A-weighted sound pressure level with annoyance ratings of "noise level," "annoyance/displeasure," "vibration/pressure," and "pulsations" in his small-scale study of wind turbine noise emissions.

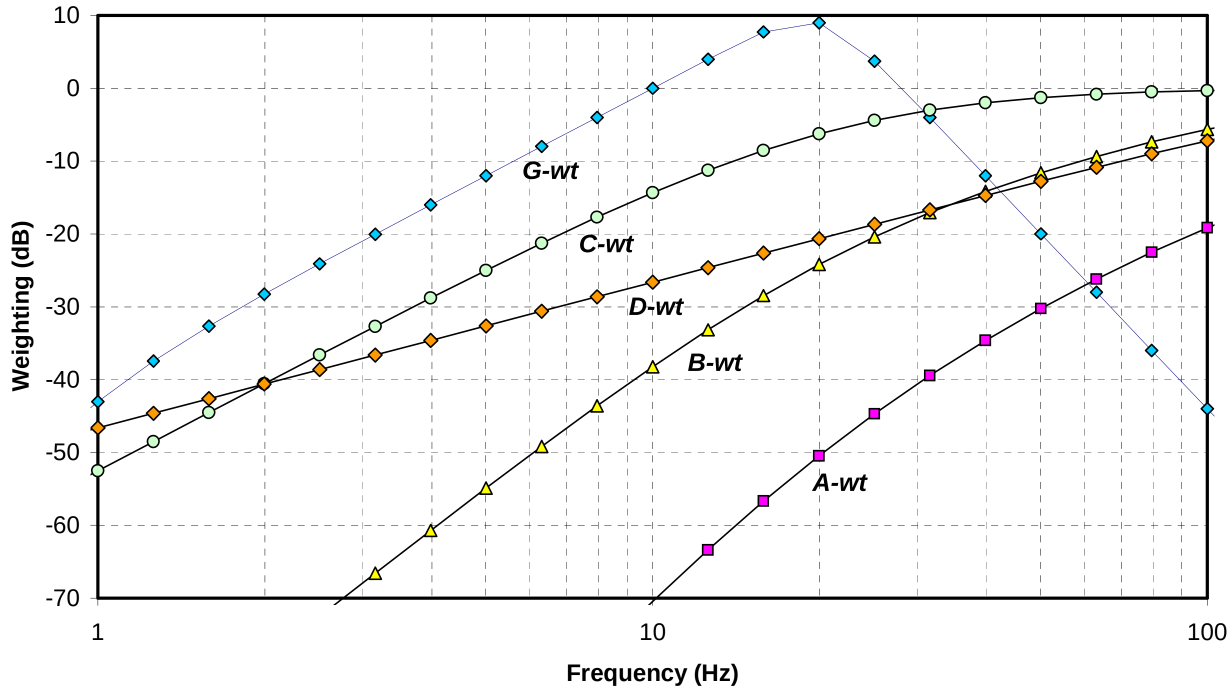


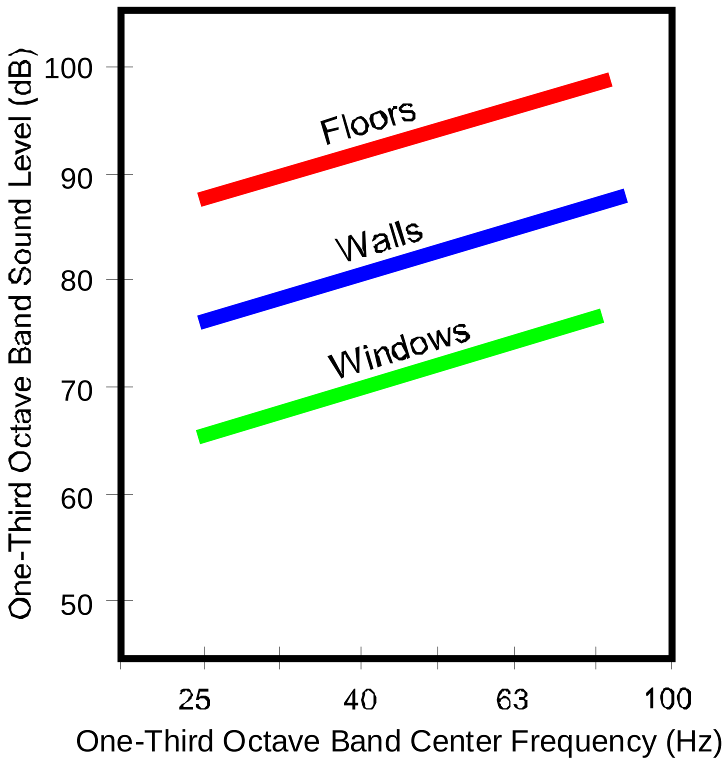
Figure 29: Frequency weighting functions of Figure 28 limited to 1 to 100 Hz frequency range.

4.1.2 Structural response to low-frequency sound and infrasound

Structural response to low-frequency sound pressures is amply documented in the technical literature as producing detectable vibration and rattle. Detectable vibration may take the form of whole body movement and/or observed vibration of light architectural elements such as large panes of glass and other vertically suspended items. Audible rattle occurs when noise-induced structural vibration causes fixtures such as doors and windows to vibrate with sufficient intensity in their frames. The vibration may also be transmitted through structural members to floors and shelving where stationary, unsecured objects (such as bric-a-brac, glassware, etc.) may rattle on the supporting member.

Hubbard's 1982 work in predicting noise-induced vibration in residential structures was seminal. Figure 30 replots Hubbard's Figure 9, which presents a family of curves showing the probable onset of perceptible vibration and possible susceptibility to rattle as a function of outdoor sound level and frequency.

Considerable research was undertaken both before and after Hubbard's work on phenomena involved in noise-induced vibration and attendant rattle. (See, for example, the summary of theoretical and experimental results prepared by Sutherland in Appendix B of Fidell *et al.,* 2000), Sutherland's summary addresses building response to noise-induced vibration; models for perception of noise-induced vibration of structures; models for production of rattle, and low-frequency aircraft noise source characteristics.



Adapted from Figure 9 of Hubbard (1982).

Figure 30: Sound pressure level thresholds for vibration and rattle (after Hubbard, 1982) in the present frequency range of interest.

The main resonant mode of most residential structures, often in the octave extending from 10 to 20 Hz (close to the fundamental frequency and first harmonic of the proposed large civil tiltrotor) is of primary importance for present purposes. The harmonic at 20 Hz, although lower in level than the fundamental, could well be a critical source of detectable vibration and rattle as well.

4.1.3 Occupational criteria

Leventhall (2003) discusses the variety of methods proposed to limit low-frequency and infrasonic noise exposure, primarily in northern European workplaces (Denmark, Germany, Poland, the Netherlands, and Sweden).[10] The various measures differ in approach, frequency bounds, reference weighting networks, rationale, and intent. Some are based on complaint histories, while others are based on audibility; some rely on *ad hoc* "adjustments" to A-weighted sound pressure levels and arbitrary "penalties" for fluctuating sounds; others are based on C- or G-weighted sound pressure levels, while yet others are based on non-standardized networks

[10] The "workplace" is not clearly enough defined to distinguish between office and factory environments. Even though intended for prolonged occupational exposure, such criteria are generally less stringent than criteria for residential or specialized architectural applications, such as assembly and concert halls.

(such as the LF, LF2, and LFNR weightings of Inukai *et al*., 1991, and of Broner and Leventhall, 1983). Differences among the various national criteria as great as 15 dB are apparent at some frequencies.

According to Pawlaczyk-Łuszczyńska *et al*. (2006), Germany, Sweden, Denmark, the Netherlands, the United Kingdom, and Poland have current or proposed criteria for occupational exposure to low-frequency noise, most of which are based on one-third octave band levels in frequency ranges from 8 to 250 Hz. (Table 2 shows the sources of these criteria, as provided by the authors. Pawlaczyk-Łuszczyńska *et al*. compare these in Figure 31.

The occupational criteria appear to be based on long-term comfort rather than health considerations, since the workplace levels are lower (by 15 dB or more) than those identified by von Gierke and Ward (1991) as adequate for acute exposures and for safety reasons. Workplace exposure levels considered tolerable on a long-term basis decrease from 110 - 115 dB to about 85 dB in the octave from 10 to 20 Hz.

Table 2: Summary of criteria reported by Pawlaczyk-Łuszczyńska *et al.* (2006)

Criterion	Description
HTL20	20 dB higher than hearing threshold level according to ISO 226:2003
DIN20	20 dB above the reference curve from DIN 45680: 1997
S70	Corresponds to Swedish recommendation for workplaces
UK18	Based on the curve proposed in the UK, but is 18 dB higher
A40	40 - A(f), where: A(f) is the response of the A-weighting frequency characteristic at the 1/3-octave band center frequency f, in dB. (*Note: the 10 and 12.5 Hz bands are shown too high by 4.5 and 4.0 dB, respectively, in Figure 31. They are corrected in subsequent figures in this report.*)

At frequencies below 100 Hz, the criteria lie within ±5 dB of one another, suggesting some degree of consensus among the governing bodies. At frequencies higher than 100 Hz, however, the HTL20 curve, reflecting the ISO 226 threshold, begins to depart appreciably from the others. Below approximately 50 Hz, the criterion levels increase at a rate nearly 70 dB per decade, or 21 dB per octave (7 dB per one-third octave band). This steep slope presumably reflects a high degree of sensitivity to frequency in this region, consistent with the slope of hearing threshold estimates in this frequency range.

Persson Waye's (2002) review of low-frequency noise occupational criteria is shown in Figure 32. Annotation for the curves may be found in Table 3. Her recommended "40"curve assumes an A-weighted, ambient sound pressure level of approximately 40 dB. The "60" and "80" curves are suggested criteria for environments with A-weighted sound pressure levels of approximately 60 and 80 dB, respectively. Persson Waye questions the foundation for the two higher criteria given present research results: "It should be observed that the curve for levels higher than 40 dBA are very uncertain as very little is known on how people are affected by LFN at those levels." (The "60" and "80" curves are not included in subsequent graphics in this report.)

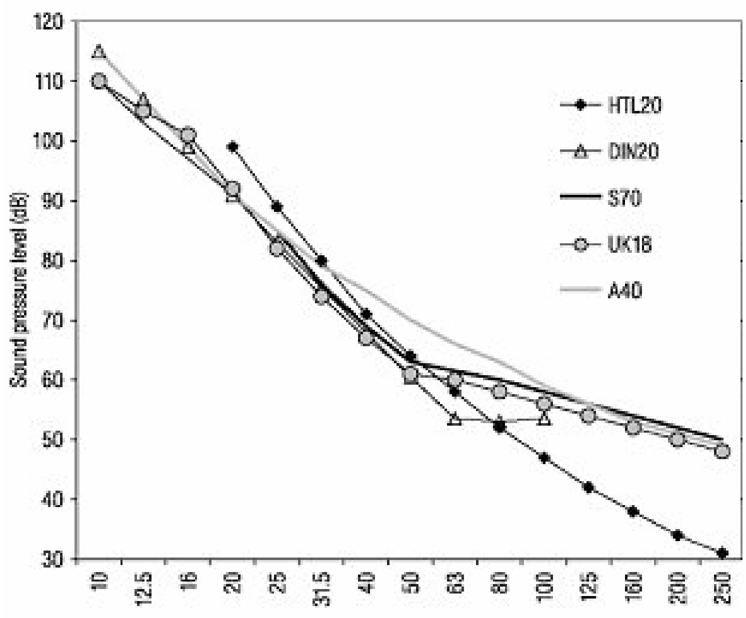


Figure 31: Comparison of criterion curves for assessing low-frequency noise in office-like areas, from Pawlaczyk-Łuszczyńska *et al*. (2006).

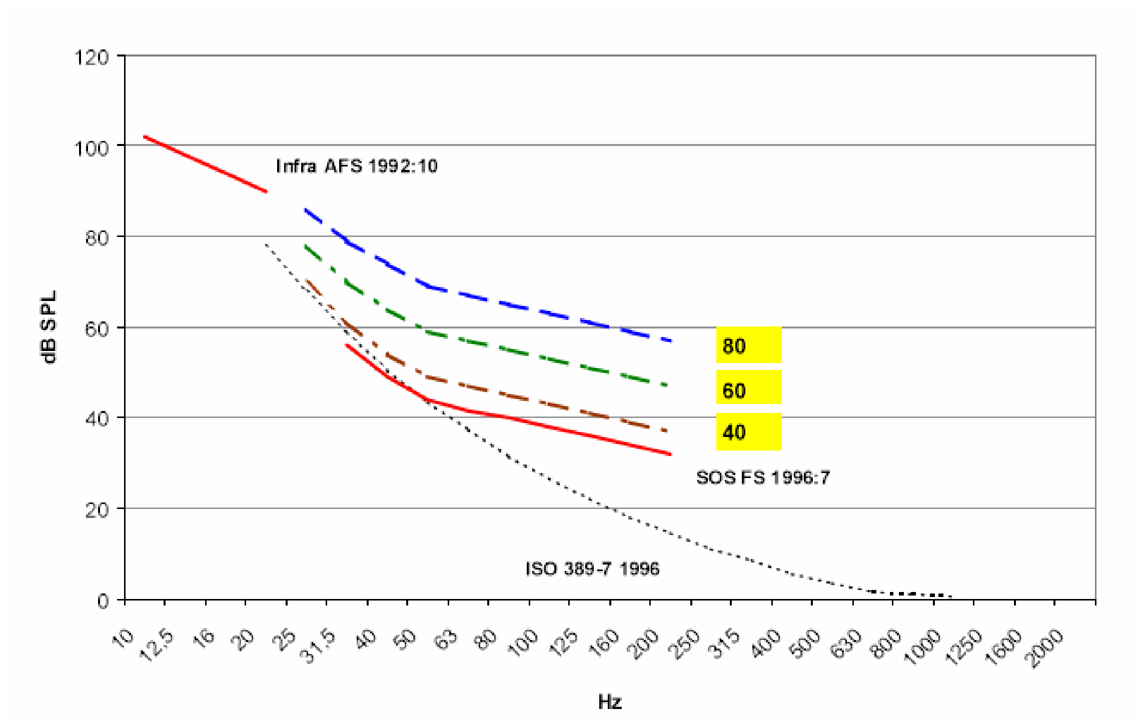


Figure 32: Recommendations for levels of low-frequency noise exposure in the occupational environment sufficient to prevent annoyance and effects on work performance (adapted from Figure 1 of Persson Waye, 2002).

Table 3: Summary of criteria reported by Persson Waye (2002)

Criterion	Description
Infra AFS 1992:10	Present regulations for infrasound in Sweden, AFS 1992:10
40	Suggested low-frequency criterion for sound environments of approximately 40 dB(A)
60	Extrapolation of suggested low-frequency criterion for sound environments of approximately 40 dB(A) to 60 dB(A)
80	Extrapolation of suggested low-frequency criterion for sound environments of approximately 40 dB(A) to 80 dB(A)
SOS FS 1996:7	Present recommendations for the general environment in Sweden
ISO 389-7:1996	Acoustics - Reference zero for the calibration of audiometric equipment -- Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions

Figure 33 plots the five workplace criteria of Figure 31 and all but the "60" and "80" criteria of Figure 32 in the format of Figure 26.[11] The criterion data points all lie above the threshold of hearing. With a few exceptions (discussed further in Section 4.1.5), the data points cluster into two groups: (1) a higher-level cluster of those for noise assessment in office-like environments (the higher-level cluster, as presented by Pawlaczyk-Łuszczyńska *et al.* (2006), together with those for workplace annoyance prevention identified by Persson Waye (2002); and (2) a lower-level cluster for the residential criteria of Moorhouse *et al.* (2005). The mean difference between the clusters varies from 12 to 18 dB. The 12 to 18 dB separation between the two seems plausible, given differences in expected ambient sound levels between residential and occupational (office) settings. Also shown is a curve depicting the average of several infrasonic hearing threshold investigations, discussed later in Section 6.4.1 (see Figure 73 on page 123). The ISO 398-7:1996 free-field threshold is also presented in the figure. Note that the lower (residential) cluster only exceeds threshold at frequencies higher than about 50 Hz.

4.1.4 Residential criteria

Møller and Lydolf (2002) cite the Danish Environmental Protection Agency (1997) as recommending that the indoor noise in dwellings not exceed a G-weighted sound pressure level of 85 dB for infrasound, and an A-weighted sound pressure level of 20 dB for low-frequency noise (10- 160 Hz).

Hessler (2005) suggests straightforward C-weighted limits for noise emissions of industrial facilities (primarily power plants) in residential areas with A-weighted tenth centile (L_{90}) ambient noise levels of 40 dB. In "normal" urban and suburban areas, he recommends C-weighted sound pressure levels of 70 and 65 dB for intermittent daytime or seasonal source operations, and for round-the-clock operations, respectively. In very quiet suburban and rural areas with the same A-weighted residual sound pressure levels (but presumably, less masking noise at higher levels), he recommends levels 5 dB lower for both intermittent and continuous operations. Hessler supports his C-weighted criteria with several complaint case studies and practical objections to narrow band acoustic measurements.

[11] Figure 33 shows the correct values for the A40 curve in the 10 and 12.5 Hz bands (see note in Table 2).

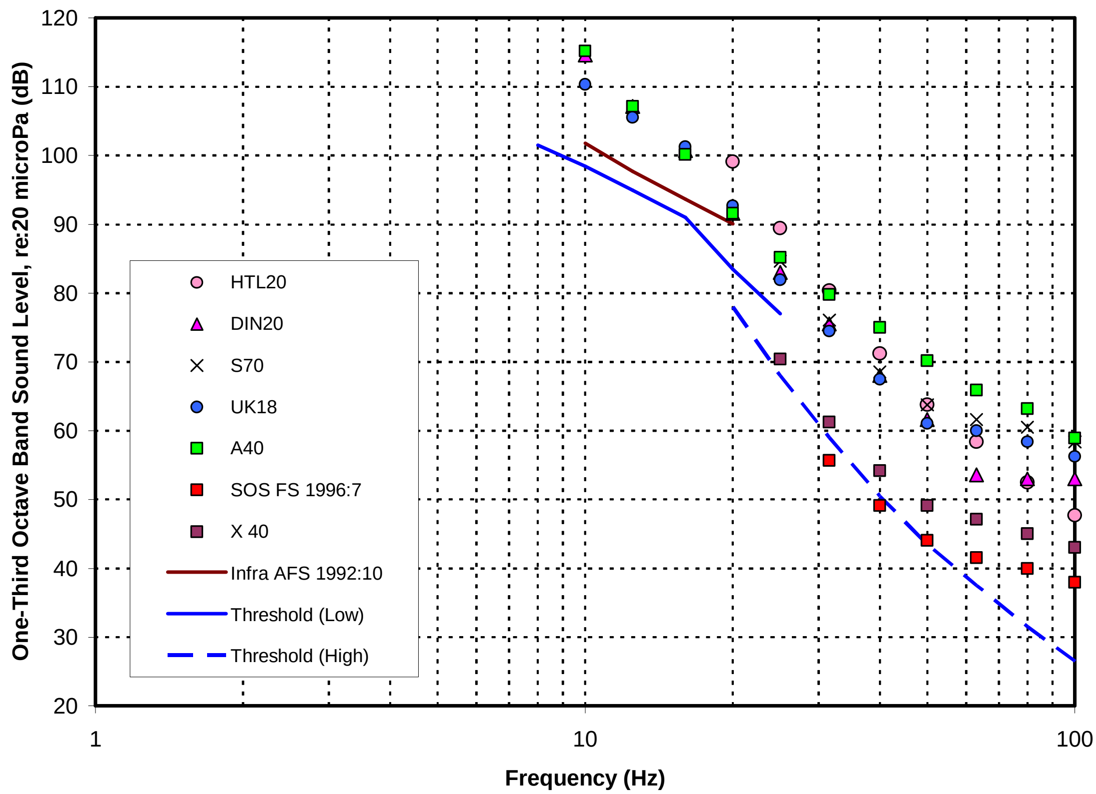


Figure 33: Comparison of low-frequency noise occupational criteria along with threshold of hearing.

Moorhouse *et al.* (2005) have proposed a criterion for residential nighttime disturbance by low-frequency noise that seeks to limit low-frequency one-third octave band equivalent noise levels to 5 dB below ISO 226 average thresholds of audibility, as shown in Figure 34. Moorhouse *et al.* recommend that daytime levels and levels of steady state low-frequency noises may exceed the "reference curve" by 5 dB; *i.e.,* reach average threshold levels of audibility.

This recommendation is consistent with the conclusion of Inukai *et al.* (2005) that "The sound pressure levels of acceptable limits ... were nearly equal to ... hearing threshold levels, and the noise levels were as low as from 21 dB(A) to 34 dB(A)" In essence, Moorhouse *et al.* assert that *no* audible infrasonic noise is acceptable in residential settings. Further, the equivalent levels in the reference curve of Moorhouse *et al.* are not only at or below audibility, but also close to (if not below in some cases) ambient low-frequency noise levels in areas of moderate population density, as shown in Figure 35.

Figure 36 replots the data of Figure 34 along with the free-field threshold of hearing per ISO 398-7:1996, and Figure 73. The figure shows that the proposed daytime criterion lies at or below the human threshold of hearing at frequencies of 25 Hz and lower, while the nighttime criterion lies at or below threshold for frequencies less than 50 Hz.

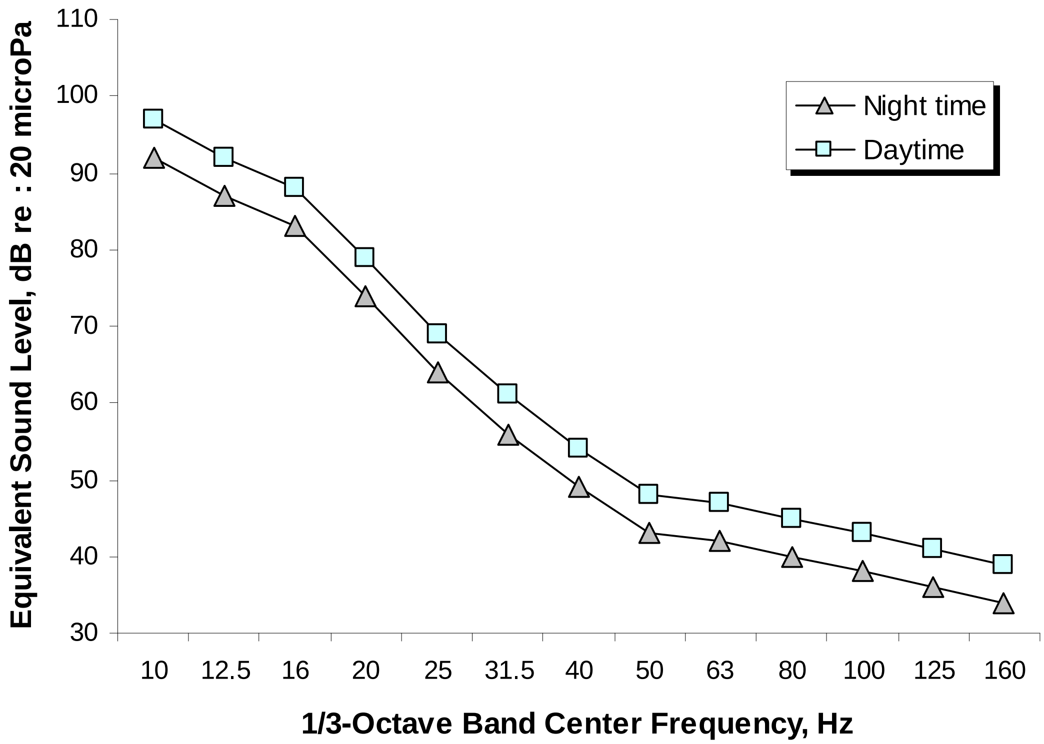


Figure 34: Daytime and nighttime residential criteria suggested by Moorhouse *et al.* (2005)

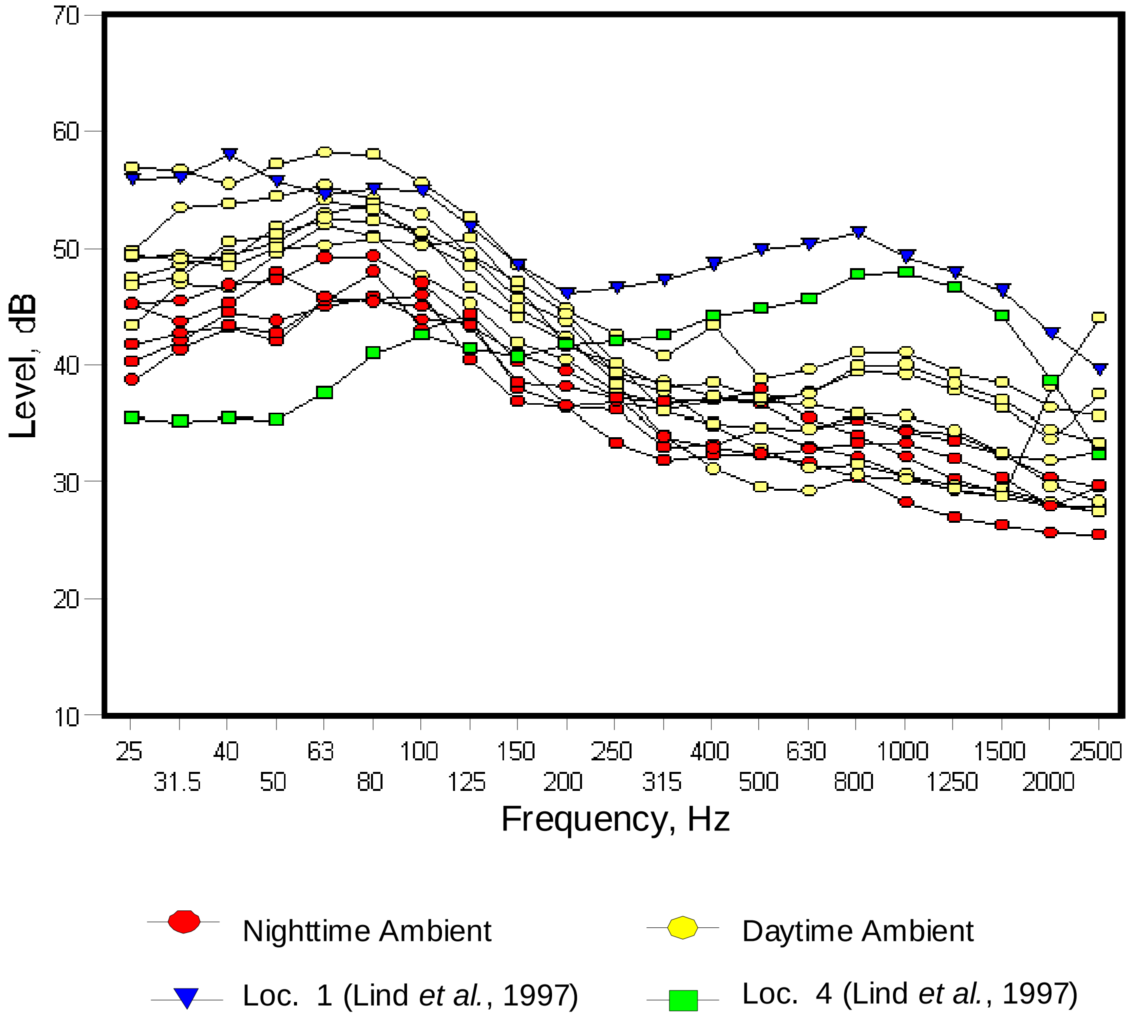


Figure 35: Daytime and nighttime ambient noise levels near an airport in a large metropolitan area (from Fidell *et al.*, 2000)

4.1.5 Suitability of occupational and residential criteria for tiltrotor cabin interiors.

Expectations of the traveling public for low-frequency noise levels in commercial air transportation could well be more stringent than the European occupational and residential exposure criteria. Figure 37 shows the combined occupational and residential criteria of Figure 31, Figure 32, and Figure 34 in a single graph. The data in Figure 37 extend over a 25 dB range in criterion values. As noted in the prior subsection, most of the Moorhouse criterion in the infrasonic region lies at or below the threshold of hearing. As a result, it is difficult to envision how these findings could be used to set interior low-frequency sound level criteria for a heavy-lift tiltrotor aircraft.

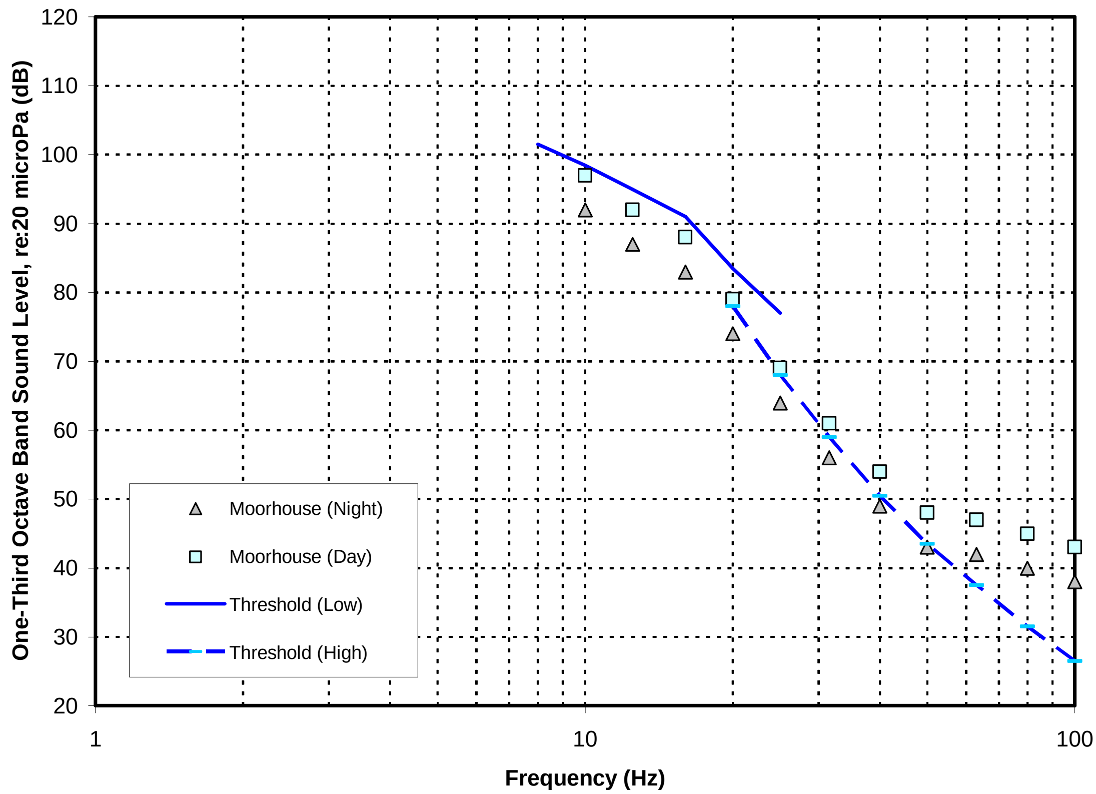


Figure 36: Comparison of Moorhouse (2005) criteria with low-frequency thresholds of hearing.

Figure 37 also shows an overlap of two data sets, as identified in Table 4. It appears that Moorhouse may have patterned his residential nighttime criterion after the guidelines of Swedish National Board of Health and Welfare (1996) for reasons cited in Section 4.1.4, and added 5 dB to obtain his daytime criterion. Persson Waye apparently chose to pattern her occupational criteria after the same Swedish standard, and added 5 dB to achieve a relatively quiet low-frequency work environment commensurate with the relatively quiet A-weighted sound pressure level of 40 dB.

Figure 38 replots the criteria of Figure 37 and adds in-flight Boeing 747 interior sound levels at three locations within the cabin during cruise. Note that at frequencies below approximately 30 Hz, noise levels in the commercial jet transport roll off at rates between 10 and 30 dB per octave, and drop below those considered appropriate for both workplace and residential environments. Assuming that these interior levels are acceptable to passengers and crew, then above 30 Hz aircraft cabin criteria should be greater than even the higher-level workplace values shown in the figure. At 30 Hz the B-747 cabin levels are on par with the workplace criteria, but below 30 Hz there is no in-cabin empirical data to provide similar guidance in the infrasonic region.

Table 4: Occupational and residential criterion equivalencies

Criterion	Same As
SOS FS 1996:7	Moorhouse (2005) residential - Night
Persson Waye (2004) "40"	Moorhouse (2005) residential – Day (5 dB higher than Night)

In-cabin low-frequency sound in the B-747 in-cabin is broadband in character, unlike the tonal character of low-frequency noise in a heavy lift tiltrotor. Likewise, the workplace and residential criteria of Figure 38 also intended as broadband criteria. If low-frequency tones are more annoying or perceived as louder than narrow bands of noise at the same level, then acceptable criterion values may be lower than those shown for the B-747 above 30 Hz. Below 30 Hz it is not clear that even the workplace criteria apply. Hence, considerable uncertainty remains in both the low-frequency and infrasonic frequency regions as to criterion values that would apply to passengers and crew in transport category aircraft for exposure durations of 30 minutes to 1 hour.

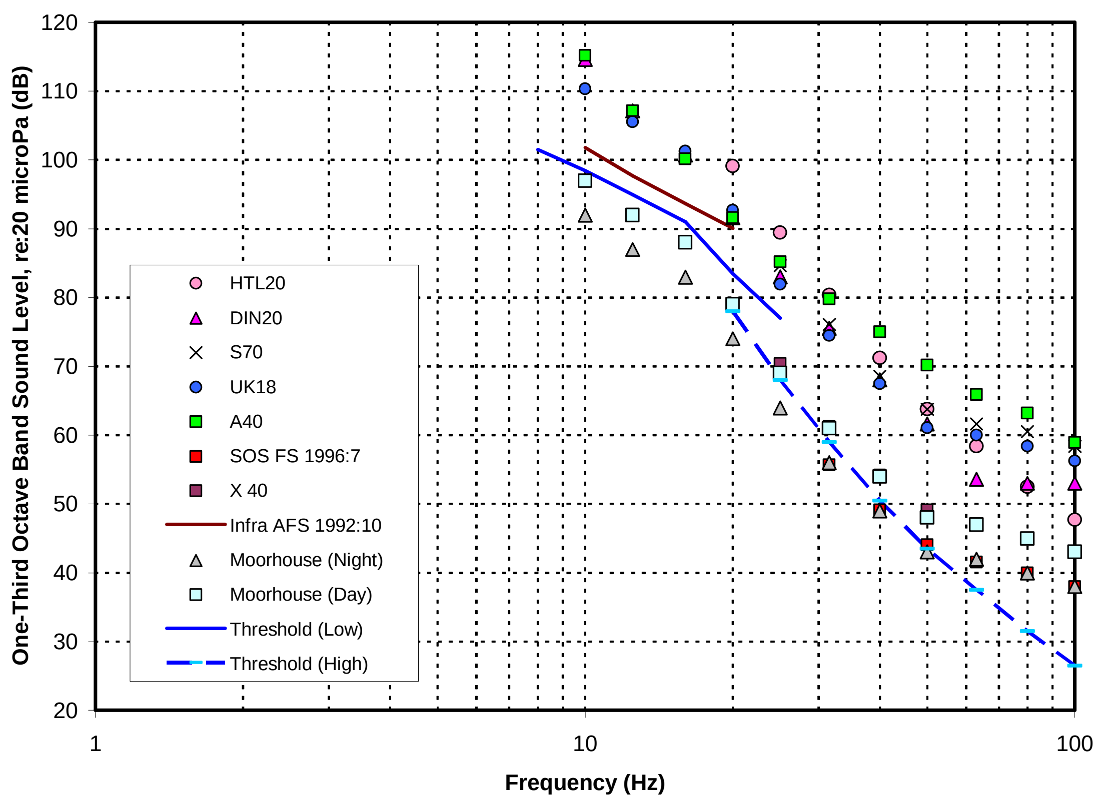


Figure 37: Comparison of combined occupational and residential criteria.

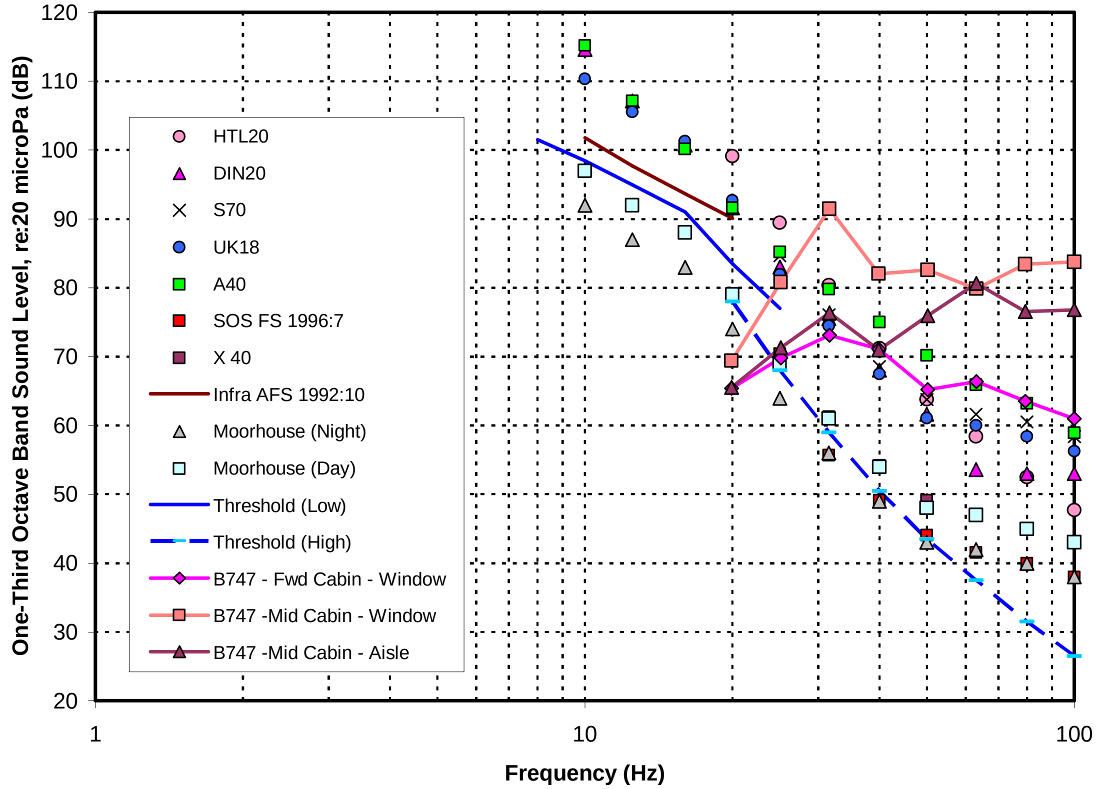


Figure 38: Comparison of occupational and residential criteria along with B-747 cabin noise.

4.2 Criteria for infrasonic exposure levels

4.2.1 Physiologically tolerable effects

Leventhall (2003) notes that the findings of the U.S. Air Force's 1960s-era studies of infrasound-induced effects lead to "endurance" criteria for exposure to low-frequency noise. Although Mohr *et al.* (1965) described a variety of unpleasant sensations that can accompany high levels of infrasonic exposure, they concluded that acute exposures to narrow and broadband acoustic energy at frequencies between 1 and 100 Hz at levels as high as 150 dB produced no gross physiological harm. Longer term (i.e., 24 hour) exposures to infrasonic levels (at 20 Hz and lower) between 120 and 130 dB were likewise considered to be tolerable on the same basis.

According to Broner (1978), Johnson's (1973, 1975) recommendations (reproduced below as Figure 39) are roughly 10 dB more conservative than Leventhall's. Johnson tolerates infrasonic exposure at levels no higher than 140 dB. Contrary to Berglund *et al.*'s (1996) speculation, however, Johnson does not view inaudible infrasonic energy as potentially harmful.

von Gierke and Ward (in Harris, 1991) suggest the "tentative" criteria reproduced below in Table 5. These criteria are based on "extrapolated data", for maximal permissible infrasonic sound pressure levels. Note that the suggested maxima were recommended for "safety" reasons (to preserve and avoid interference with general bodily functions), for people familiar with infrasound, and without regard for comfort, annoyance, or communication interference.

Although they might arguably be useful as upper limits for tiltrotor crew exposure, they are almost certainly inappropriate for commercial passenger service. The tabulated values closely resemble Nixon's (1973) recommendations, as illustrated in Figure 40.

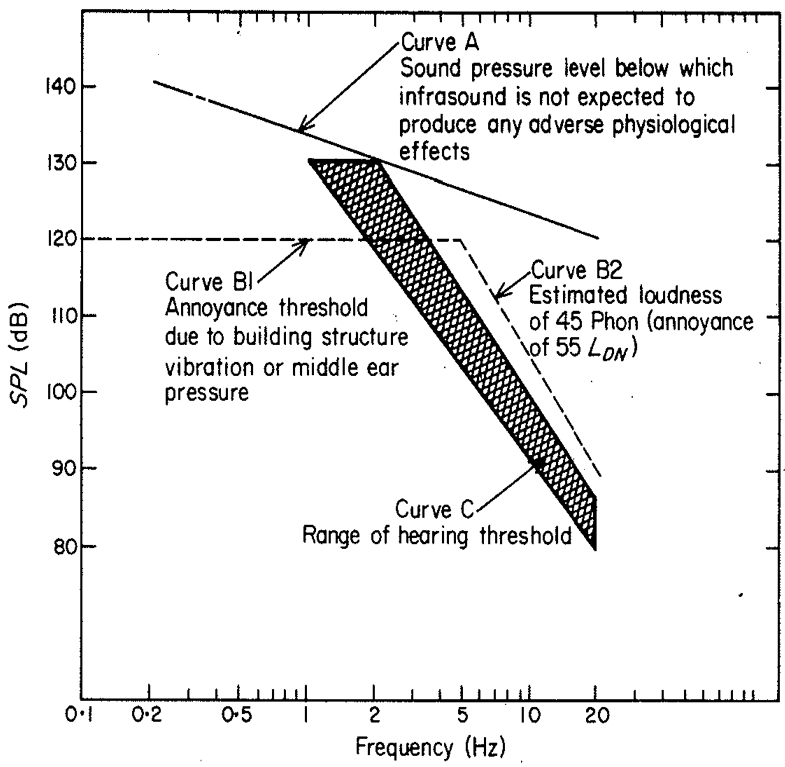


Figure 39: Criterion proposed by Johnson (from Broner, 1978)

Table 5: Maximum permissible infrasonic sound pressure levels (from Harris, 1991)

Duration	Sound Pressure Level by Frequency, in dB			
	1 Hz	5 Hz	10 Hz	20 Hz
1 hour	145	138	135	132
8 hours	136	129	126	123
24 hours	131	124	121	118

4.2.2 Annoyance

Since an acoustic environment that satisfies a criterion for avoiding lasting physiological harm does not necessarily yield a comfortable working or traveling environment, such a criterion is not particularly helpful as design guidance for cockpit and cabin design for a commercially viable tiltrotor aircraft. Workplace and residential criteria for infrasound exposure are somewhat more apt for such purposes, although the circumstances and duration of exposure in these settings also differ from those of present interest. Acceptability criteria for workplace exposure are usually formulated for a lifetime working career, while those intended for residential exposure are usually intended to accommodate prolonged rest and relaxation. People who

choose to travel on tiltrotors will do so primarily for purposes other than rest and relaxation on board an aircraft, and for relatively brief periods of time.

Broner (in Crocker, 2007) asserts that exposure to infrasound at levels between 90 to 110 dB is generally only “potentially” annoying, and is unlikely to be accompanied by unpleasant side effects. For short exposure durations, the range between the recommendations of von Gierke and Ward on the one hand, and Broner on the other, is thus roughly 20-35 dB. (For prolonged exposure to infrasound, the range between innocuous and unsafe exposure to infrasound is much narrower.)

4.3 Adaptation of LFSL metric to tiltrotor applications

The field studies described in Sections 6.3.1 and 6.3.2 have come closest to yielding a dosage-effect relationship similar in nature to the one endorsed by FICON (1992) to assess impacts of higher frequency transportation noise. The predictor variable of FICON’s relationship is a time-weighted, 24-hour average sound level, whereas the predictor variable of the more recent studies is a single-event metric (LFSL), tailored to the low-frequency noise emissions of the engines of large jet transport aircraft. The 25-80 Hz range of LFSL is thus insensitive to the acoustic energy at the fundamental frequency and first harmonic of tiltrotor noise.

Before LFSL can be applied to predicting the prevalence of community annoyance with tiltrotor noise, consideration should thus be given to extending its lower frequency limit so that the metric encompasses the fundamental rotor passage frequency; *i.e.,* to the 10 Hz one-third octave band. Table 6 illustrates the differences between original and extended range LFSL values for the tiltrotor spectra shown in Figure 18 and Figure 20 (see Section 1.3.6 for discussion).

Figure 41 replots the mean dosage-response regression line through the results of the LAX and MSP studies illustrated in Figure 70 on page 117. Figure 41 uses this mean regression line to predict the percentage of people likely to by highly annoyed to the LFSL 1 values for fore and aft observer locations identified in Table 6. This plot suggests that even without considering noise energy in the 10 and 20 Hz one-third octave bands, about one quarter or more of people in communities in tiltrotor operating areas can be expected to be highly annoyed by induced secondary emissions in residences. Although the LAX and MSP studies shed no light on the consequences of yet-more-efficient induction of secondary emissions produced by rotor noise at frequencies close to resonances of wood frame structures, it seems likely that additional rattle would further increase annoyance prevalence rates. As discussed in Section 5, these predictions require empirical confirmation via one or more controlled exposure field studies.

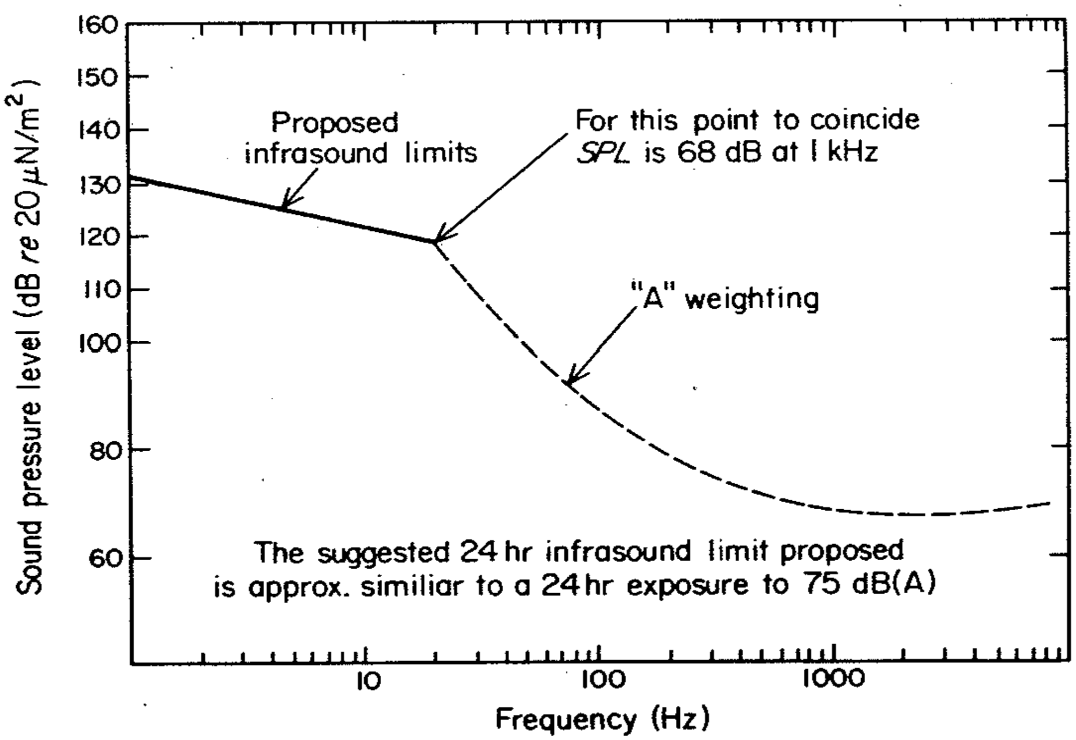


Figure 40: Nixon's (1973) recommendation for 24-hour exposure limits (extrapolated from 8-minute exposures), adapted from Broner (1978).

Table 6: Comparison of low-frequency spectra with various frequency-weighted sound pressure levels for tiltrotor in hover configuration.

	One-Third Octave Band Sound Pressure Levels (dB)										Frequency-Weighted Sound Pressure Levels (dB)					
Freq.	10	12.5	16	20	25	31.5	40	50	63	80	Linear	A-level	C-level	G-level	LFSL 1	LFSL 2
Fore	92.0	----	----	76.0	72.1	----	69.3	73.9	69.9	71.2	92.4	54.2	81.0	92.9	78.6	92.3
Aft	92.0	----	----	76.0	77.7	----	83.8	87.1	82.5	85.7	95.2	68.9	91.5	93.2	91.3	94.8

Notes:

Fore = Forward-looking 30 degree angle of depression from aircraft longitudinal axis, 500 feet above ground level.

Aft = Rearward-looking 30 degree angle of depression from aircraft longitudinal axis, 500 feet above ground level.

LFSL 1 = power summation of 25 through 80 Hz one-third octave bands.

LFSL 2 = power summation of 10 through 80 Hz one-third octave bands.

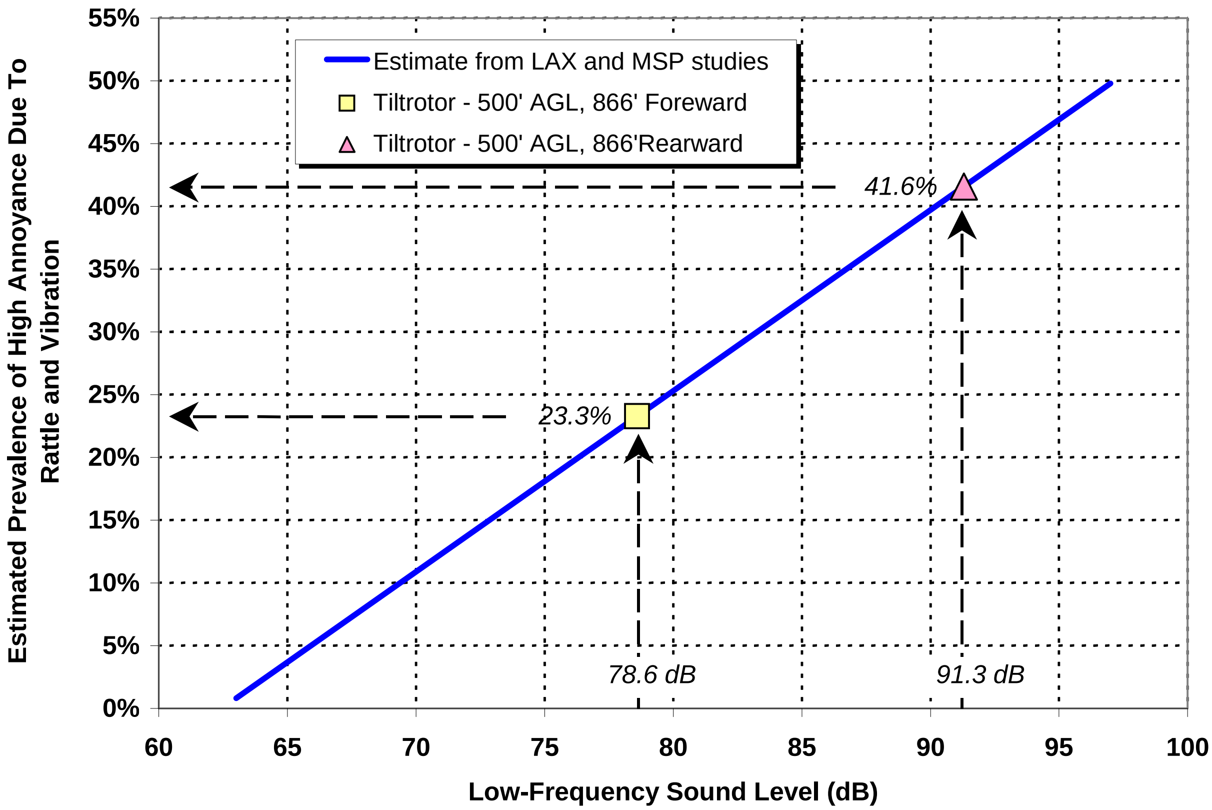


Figure 41: Estimated tiltrotor-induced prevalence of high annoyance due to rattle and vibration in the vicinity of heliports.

5. RESEARCH RECOMMENDATIONS

This section describes applied research intended to produce information useful for assessing the effects of tiltrotor noise on crew, passengers, and communities. Both field and laboratory studies are suggested: the former to clarify effects of tiltrotor noise in residential areas near airports and other operating areas; and the latter to investigate the acceptability of onboard noise effects.[12] The recommended studies are discussed in general terms below.

Experimental designs are *de facto* economic exercises, whose goals are to purchase as much information, of as high quality, as research budgets permit. Details of the inevitable compromises between ideal and affordable study designs are described in separate Appendices to this report for each recommended project.

5.1 Rationale for study of community reaction to tiltrotor-like noise

The estimates of Section 4.3 indicate that tiltrotor noise is likely to annoy a considerably greater proportion of the residential population living near tiltrotor operating areas than warrants federal funding of aircraft noise mitigation projects (*i.e.*, the predicted proportion of the population highly annoyed by noise exposure at a value of L_{dn} = 65 dB).

FAA's policy for funding noise impact mitigation programs in neighborhoods in which aircraft noise exposure exceeds L_{dn} = 65 dB is explicitly based on FICON's 1992 dosage-effect relationship, illustrated in Figure 42. According to FICON's dosage-effect relationship, 12.3% of the population is highly annoyed at a level of L_{dn} = 65 dB. The corresponding value of LFSL (that is, the value of LFSL at which 12.3% of the population is highly annoyed by rattle induced by low-frequency noise), as calculated from the relationship seen in Figure 70, is 71 dB. This is a conservative calculation, since it is readily apparent that FICON's dosage-effect relationship *under*estimates the actual prevalence of annoyance with aircraft noise by a factor of two in the vicinity of L_{dn} = 65 dB (Fidell, 2003; Fidell and Silvati, 2004).

Since the calculations of Section 4.3 suggest that tiltrotor operations may create LSFL values as much as two orders of magnitude greater than LFSL = 71 dB in the vicinity of tiltrotor landing areas, it is important to verify the utility of LFSL as a predictor of annoyance due to rattle associated with tiltrotor applications.

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[12] As discussed in Section 1.3.8, the very low levels of low-frequency noise that large tiltrotors are expected to generate during cruising flight away from the immediate vicinity of landing areas minimize needs for studies of outdoor recreational noise impacts.

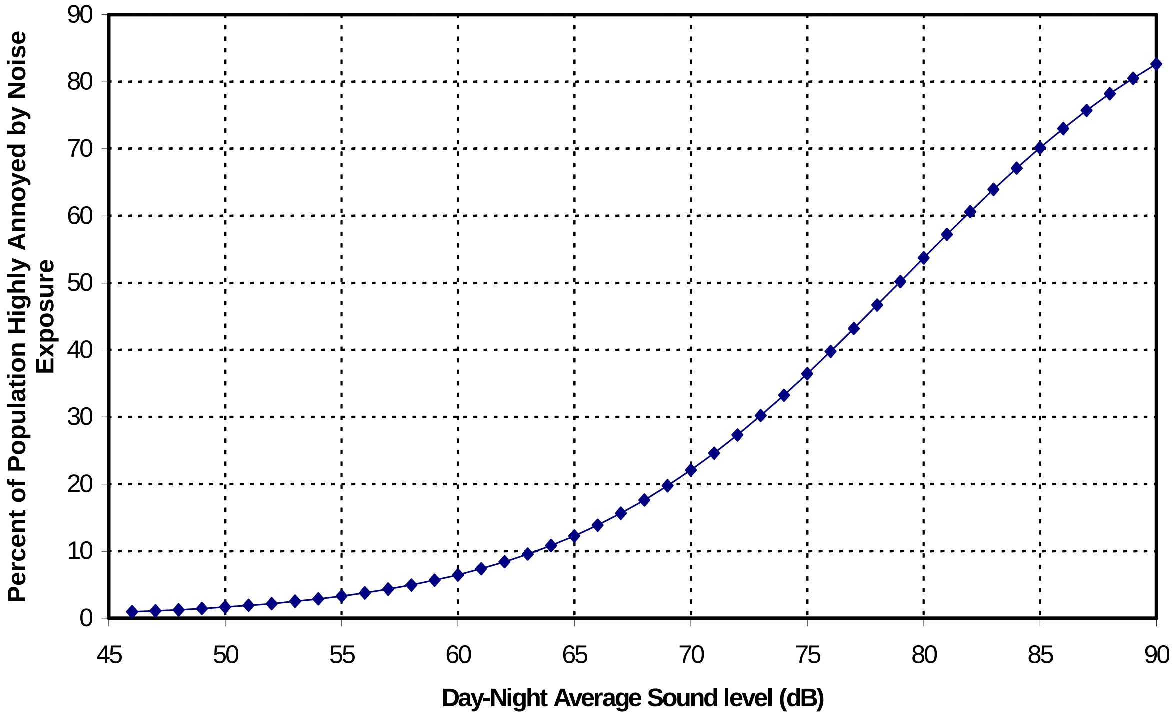

Figure 42 FICON's (1992) dosage-effect relationship

5.2 Prevalence of residential annoyance with rotorcraft noise

The most pressing research need is for empirical and quantitative understanding of the residential annoyance of infrasonic and very low-frequency noise, and of induced secondary emissions (rattle). Social surveys should be undertaken in which interviews are conducted with residents of at least one (but preferably more) neighborhood(s) with controlled outdoor exposure to infrasonic noise as similar as feasible to that of large tiltrotors. The goal of such research is to permit prediction of the prevalence of a consequential degree of community annoyance with tiltrotor noise from a demonstrably useful measure of low-frequency noise exposure.

Many residences must be simultaneously exposed to simulated tiltrotor noise in a large-scale, intentional exposure field study. The obvious pre-requisites for such a study are 1) a portable device capable of producing a reasonably faithful simulation of the infrasonic and low-frequency portions of a tiltrotor noise signature; and 2) one or more residential areas in which arrangements can be made to permit conduct of a social survey.

In order of similarity to tiltrotor noise, options for this sort of field study are 1) noise created by a controlled schedule of heavy-lift helicopter operations; 2) noise created by some other controlled simulation of low-frequency rotor noise; and 3) adventitious exposure to noise created by extant (uncontrolled) helicopter operations. Although both observational and experimental approaches are plausible, the experimental approach is preferable for reasons noted below.

Appendix D contains a detailed study design for an experimental field study in which the noise of heavy lift helicopters serves as a surrogate for tiltrotor noise. Use of rotorcraft in such a study confounds community reactions to low-frequency noise with community reactions to nearby flight operations, but may also come closest to simulating the full, real-world experience of proximity to tiltrotor operations.

Appendix E describes the effort required to develop a field-portable device that can simulate the low-frequency noise emissions of tiltrotor operations. By divorcing the noise emissions of tiltrotors from the experience of flight operations, use of non-flying noise simulators permits evaluation of the noise impacts of tiltrotors independently from all of their other influences on communities.

5.2.1 Intentional exposure social surveys relying on controlled operations of a heavy-lift helicopter as a surrogate noise source

The infrasonic noise emissions of the CH-47 military heavy lift helicopter are fairly similar to those of a heavy lift tiltrotor, since its fundamental blade passage rate is within a one-third octave of the tiltrotor (11.3 Hz for the CH-47 vs. 9.3 Hz for the notional civil tiltrotor). The gross weight of the heaviest CH-47 models is less than half that of the proposed heavy lift tiltrotor, however, so its absolute levels are somewhat lower than those of the tiltrotor, and phase relationships among the CH-47's counter-rotating rotors and its higher-frequency emissions also differ from those of the tiltrotor.

Likewise, the low-frequency emissions of the S-64 (a six-bladed heavy lift civil helicopter) also differ in detail from those of a future tiltrotor, but might be sufficiently similar in essentials to serve as a surrogate for a tiltrotor in a field study. The greater problems with using any heavy lift helicopter as a surrogate for a tiltrotor in a field study of noise impacts in residential neighborhoods are pragmatic and logistical. As discussed in Appendix D, flight time costs for heavy lift helicopters will total many hundreds of thousands of dollars; considerable difficulties will be encountered in locating suitable residential areas for multiple daily landings and takeoffs over extended periods; and several safety of flight and ground safety concerns will have to be resolved.

5.2.2 Alternative controlled-exposure social survey

A variety of workarounds to the practical difficulties of using heavy lift helicopters to simulate tiltrotor flight operations in residential neighborhoods merit consideration. All involve reliance upon a transportable device capable of creating controlled, high intensity, wide-area, low-frequency acoustic energy under free field conditions. An ideal system for present purposes would be relatively simple, small, self-contained, and inexpensive; highly reliable (*i.e.*, robust, low maintenance, inherently safe, and capable of remote, all-weather, unattended operation); and capable of producing a least 1,000 acoustic watts of minimally distorted, non-directional energy from 10 to 100 Hz, with at least a modicum of control over harmonic content.

A number of electromechanical, chemical, steam-driven, aerodynamic and other approaches (*cf*. Park and Robertson, 2009) have been pursued in various contexts to create devices with some of these characteristics. All such systems developed to date have limitations or operational characteristics that render them less than ideal for present purposes. A different sort of device might suffice for the more limited and specific goal of simulating very low-frequency tiltrotor

noise emissions, however.[13] Four such design approaches that might plausibly be developed to simulate low-frequency rotor noise are discussed below.

A. Electrodynamic air modulator and coupling horn

High-pressure air modulators of varying designs have been widely used in aerospace acoustic testing applications for decades. These devices are capable of accurately and reliably producing extremely high acoustic power levels over a wide frequency range. Two major disadvantages for present purposes are 1) the need for a very large output coupling horn, and 2) the need for considerable auxiliary equipment.

An output coupling horn adequate to reproduce the 9.3 Hz tiltrotor fundamental will be unavoidably large. Taking an exponentially flared horn as a design example, the horn length is determined by 1) the horn flare rate and 2) by the desired diameter at the horn exit. The flare rate m of an exponential horn determines the rate at which the horn's cross-sectional area increases with distance from the horn throat, and is fixed by the throat area and the desired horn cutoff frequency, f_c, defined as follows:

$$S(x) = S_t e^{mx}, \quad where \quad m = \frac{4\pi\, f_c}{c_0}$$

Equation 1

A rule of thumb for estimating the horn exit diameter is that $k_c r_m = 1$, or that the mouth radius must be approximately equal to $\lambda_c / 2\pi$. An exponential horn for which $f_c = 9$ Hz would be about 30 meters long, with an exit diameter of nearly 12 meters. Such dimensions are intrinsically impractical for a readily transportable system. While much attention has been paid to horn design in the last 50 years – particularly in reducing horn sizes and mitigating the resultant trade-offs - the design of a compact horn that retains acceptable acoustical performance remains challenging.

Given the very high power densities of air modulators, distortion and nonlinear effects (*e.g.*, shock formation in low flare-rate horns) would also require careful attention during design and testing phases. Exponential horns are also increasingly directional with frequency, such that off-axis homes to be insonified in field settings would experience a gradual shift in the balance between the fundamental and higher harmonics of test signals. This could potentially lead to restrictions in the size of the study sample area, as test subjects located at various sideline distances from the horn centerline would experience different shifts in the balance between the fundamental and higher harmonics. Acceptable limits on such shifts would have to be considered in a horn design trade-off study.

[13] Note that it is not necessary to faithfully emulate rotor pulse shapes at all frequencies simply to investigate infrasonic noise effects. If the issue of concern is the annoyance of rattle caused by noise induced, structureborne vibration, the acoustic energy of the pulse is of much greater concern than its shape. At the fundamental frequency and at residential distances of current interest, the shape of an inaudible rotor pulse is of little relevance. Further, if the issue is the direct annoyance of short duration impulsive signals at higher frequencies, it has been shown (Fidell *et al.*, 1970) that the energy content of individual pulses, rather than their shapes, control annoyance judgments.

In addition to a very large coupling horn, a complete air modulator-based, low-frequency rotor noise simulator system would require considerable auxiliary equipment. The support requirements include a large (200 horsepower or greater) engine- or generator-driven compressor to provide primary air; an electric generator for the drive electronics; power supplies and power amplifiers for the air modulator's field- and drive coils; and depending on the transducer used, separate air and/or water supplies for the transducer's cooling system. This auxiliary equipment further complicates the transportability, maintainability, and overall convenience of field operation of an already-large and complex simulation system.

B. Combustion noise sources

Chemically-enhanced (expanding gas) noise production is another potential source of high-level, low-frequency noise. Two forms of such combustion noise are discussed briefly below: open flame oscillatory noise, and pulse jet noise.

Open flame oscillatory noise

Periodic pressure fluctuations are an undesirable condition in applications involving large flow volumes of air and exhaust gas in industrial-scale burners, furnaces, and engines. According to Mugridge (1980), "Interaction between heat fluctuations and the internal standing wave field at one of the natural frequencies of the air column produces strong organ pipe tones." Continuous, combustion-driven oscillations can be sustained (if not reinforced) by several acoustic feedback mechanisms within the burner and/or air and vaporized fuel intake components. If heat release fluctuation rates match one of the natural acoustic modes of ductwork, very large amounts of acoustic power may be produced. The phenomenon is known as "flow-acoustic lock-on", or more generically, "singing flames" (Seebold, 2004).

Sub-sonic, combustion-driven oscillation noise is well enough understood that systems could in principle be designed to generate high sound levels at low frequencies. High efficiency chemical or thermal energy to noise ratios can be achieved, especially using pulse combustors (Putnam, 1976). The critical design variable is enclosure of the flame in a resonant tube or cavity. With appropriate impedance mismatches at either end of the effective duct, and with sufficient flame energy input, substantial acoustic pressures can be achieved. If the duct contains a Helmholtz resonator, then the acoustic pressure fluctuations may be radiated to the outside world.

The utility of a device for producing open flame oscillatory noise for present purposes is doubtful. It would have to be constructed (and later demolished) on site, of heavy and heat-resistant materials. It would also pose multiple design and development risks, require sizable fuel storage facilities, would be difficult to operate on an intermittent schedule, and could not be operated unattended due to safety-related concerns. Tailoring the harmonic structure relative to resemble that of a tiltrotor would also be problematic.

Pulse jet noise

Pulse jet engines, best known for their use in the V-1 "buzzbomb" early cruise missile, are mechanically simple resonant combustion engines. Although SNECMA produced a scalable design for a valveless pulse jet decades ago (Kentfield, 1993), and NASA's Glenn Research Center and jet engine manufacturers have conducted research on pulse jet (subsonic combustion)

and pulse detonation (supersonic combustion) jet engines for years, they remain far from practical aeronautical applications other than in target drones and hobbyist uses.

Pulse jet engines are basically tubes with carefully shaped combustion cavities that are sealed at one end (either by valves or aerodynamic forces) and open to the atmosphere at the other. They operate as internal combustion engines that sequentially admit and ignite air/fuel mixtures in the combustion cavity, and expel pressurized combustion gasses at the open end of the tube. The sequence of induction/fuel injection, ignition, combustion, and exhaust is controlled by periodically alternating low and high-pressure phases in the combustion cavity.

Design variants have been produced with and without mechanical valves and direct fuel injection. For pulse jets between about 1 foot and 10 feet long, the low and high-pressure phases in the combustion cavity typically alternate at rates from hundreds to tens of Hz, producing, in addition to thrust, very high levels of noise rich in harmonic tonal content.

A pulse jet's fundamental firing frequency is determined by its dimensions. The V-1 engine, which operated at about 40 Hz, was 12 feet long. A version capable of operating at 10 Hz would be on the order of 50 feet long. Because combustion in a pulse detonation engine is not resonant, but is controlled by its spark firing rate, its fundamental exhaust note is not as closely linked to its size. Pulse detonation engines are considerably more complex than simple pulse jets, however.

For purposes of simulating tiltrotor noise in residential settings, the most attractive property of pulse jets is the very high sound levels that they produce. Their disadvantages include their size, potential difficulties in starting them, high operating temperatures, safety concerns associated with handling of explosive fuels, and the needs and risks of further development effort to optimize them for field use.

C. Low pressure/high volume siren

A different approach to simulating high-level, low-frequency tiltrotor noise is a high-volume/low-pressure siren powered by industrial-scale axial blowers and a mechanically driven siren plate. Such a system could be designed to act as an acoustic monopole, with an output power *W* dependent only upon frequency and the net volume velocity produced at the siren outlet:

$$W = \frac{\rho c k^2 Q^2}{8\pi(1 + k^2 a^2)}$$

Equation 2

where k is the wave number, Q is the acoustic source strength and *a* is the effective radius of the sound source. Two possible configurations for such a high-Q sound source suitable for very low-frequency operation are briefly described for purposes of illustration.

The first configuration consists of a high-volume, fan-driven recirculating duct incorporating a siren section composed of an elliptical cam plate rotating on-axis within the duct at the desired fundamental frequency. As the cam plate rotates through each full revolution, it alternately directs the fan outlet into an exhaust port, then progressively entrains air from the same port into

the fan inlet. Unlike most air modulators, the net flow from the system is zero. Very high volume velocities can nonetheless be achieved, which is exactly what is needed to generate acoustic power at low frequencies. The design also permits dynamic profiling of the outlet port to control (within limits) the harmonic content of the siren.

A variant configuration that might also serve present purposes would employ a similar large capacity axial blower, installed in two concentric, circular ducts separated into low- and high-pressure sides. Both ducts are closed off at one end by a common siren plate. The siren plate rotates at a submultiple of the desired fundamental frequency, alternately connecting the high- and low-pressure duct sections to the exhaust port.

Figure 43 and Figure 44 are schematic illustrations of the two design variants described above. In both alternatives, the noise generators make use of very high volume but relatively low pressure blowers to develop the large values of Q needed to generate high sound power levels at 10 Hz. Using the first configuration as an example, a power output of 1000 acoustic watts at 10 Hz would require a Q of 47, corresponding to a minimum sustained duct delivery of 98,000 cfm. A value of Q twice as large would provide four times the power.

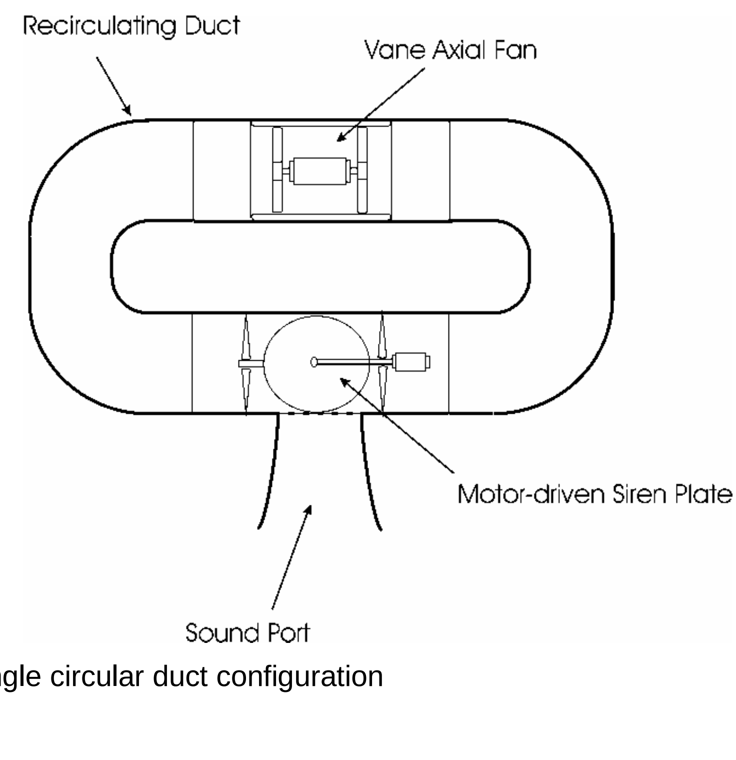

Figure 43: Single circular duct configuration

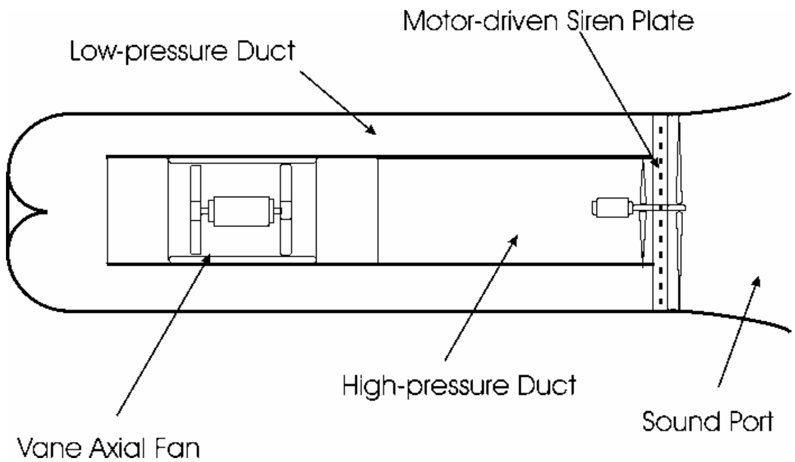

Figure 44: Dual concentric duct configuration

With careful design attention to minimizing pressure and duct losses, the necessary delivery rates are readily achievable using commercially available fans. As a low-pressure system, this approach largely avoids the nonlinearities and distortion problems associated with conventional high-pressure sources such as air modulators. This system will require a large, engine-driven generator to power the duct fan(s) and the siren motor, but little else in the way of support equipment.

D. Rotor whirl stand

Figure 45 is a sketch of a single bladed rotor whirl stand concept. A single bladed rotor with a matching counterweight spins at relatively high tip Mach numbers to radiate high in-plane noise levels. The single-bladed rotor keeps the fundamental frequency low in order to simulate a larger 4 bladed tiltrotor aircraft. The rotor blade can in principle be designed in a variety of ways to give the desired character of low-frequency noise typical of a large full-scale tiltrotor aircraft.

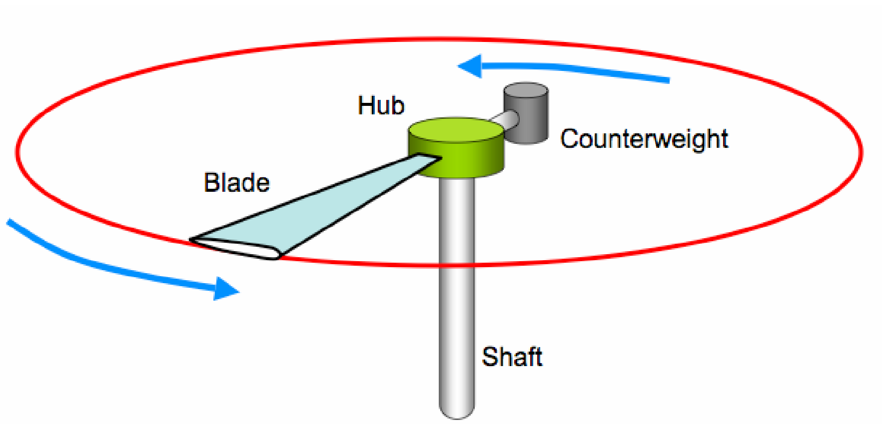

Figure 45: Conceptual diagram of a single bladed rotor harmonic noise generator

As discussed in Section 1.3, the fundamental frequency of a large tiltrotor aircraft is roughly 10 Hz. Two ways of generating this type of radiating noise from this type of apparatus are 1) through rotating thickness (monopole) noise sources, and 2) through rotating force (dipole) noise sources. The harmonic noise of a large tiltrotor aircraft can be approximated by using a combination of both types of sources.

Monopole Source

Figure 46 illustrates the noise that can be produced by a rotating blade with a rather large cross section. To obtain very low frequency and high acoustic power levels, a single bladed nearly non-lifting relatively high tip Mach number rotor is proposed. Assuming a nominal operational tip Mach number of 0.65,

$$M_T = .65 = \frac{\Omega R}{a_0} \quad \text{and} \quad f\left[Hz\right] = \frac{\Omega}{60}$$

Equation 3

where Ω is the rotor RPM, R is the rotor radius, and a_0 is the speed of sound. Solving for the rotor radius for a fundamental frequency of 10 Hz yields:

$$R = \frac{.65 \cdot 1{,}100}{60 \cdot f} = 11.9 \approx 12\,ft \text{ radius.}$$

Equation 4

Assuming that the rotor blade thickness is 18% of chord and the chord is 2-4 ft, the peak (negative) acoustic pressure of thickness noise produced by this single bladed rotor at a distance of 150 feet from the rotor hub is about 10-30 Pascals. A time history of the resulting pulse is shown below in Figure 46 for 1/4 revolution of the rotor.

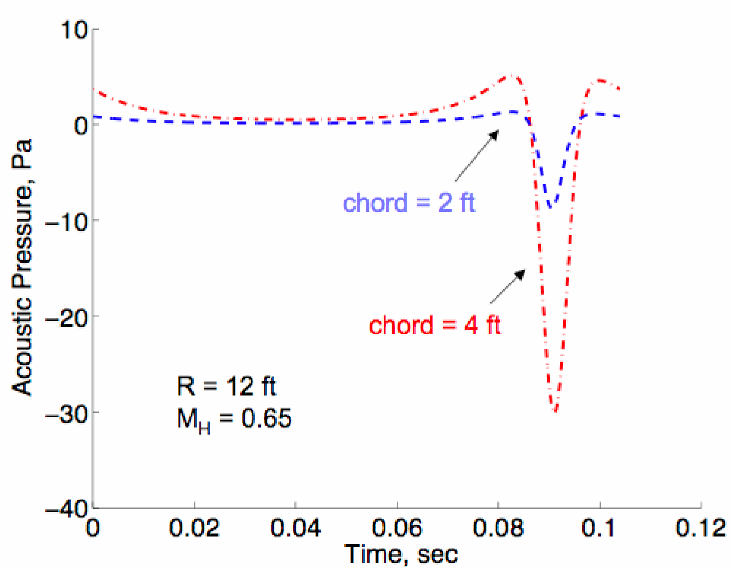

Figure 46: Time history of noise pulse generated by a single bladed rotor harmonic thickness noise generator

Because the rotor is non-lifting, the noise produced by this simulator does not contain any lift dipole sources. The pressure drag noise produced by the rotor has also been neglected. The result is the classical thickness noise pulse, which radiates mostly at low frequencies near the plane of the rotor. The levels produced by this device are more than adequate to simulate the levels produced by a large full-scale tiltrotor aircraft. However, the pulse shape of the simulation device is different from the pulse shape of a large tiltrotor aircraft flying overhead. These differences are a direct result of trying to use thickness noise to simulate the loading noise of the large tiltrotor aircraft.

This observation is illustrated more clearly in Figure 47, where the harmonic levels of the thickness noise are shown. While the levels are high, when compared to those estimated in Section 3.1 for the large tiltrotor aircraft, they do not replicate the fall off in levels with increasing harmonic number that are typical of a tiltrotor aircraft operating in a clean configuration. They more typically represent the noise that might be produced by a tiltrotor experiencing harmonic re-circulation noise or BVI noise.

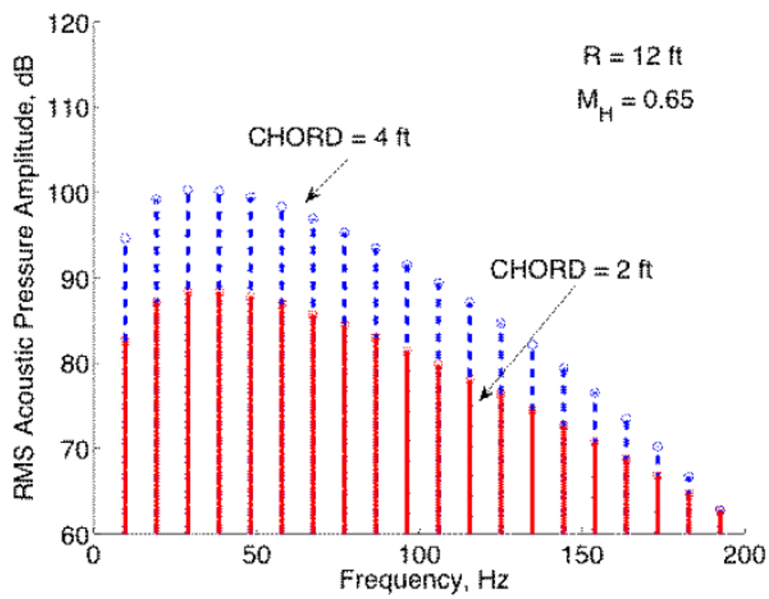

Figure 47: Power Spectra of the Simulated Tiltrotor

However, these noise levels can be modified if desired by designing different operating arms and corresponding counterweights. Longer arms would increase the noise levels, while shorter ones would decrease them without dramatically changing the low frequency character of the radiated noise, as long as the tip Mach number of the single bladed rotor is not allowed to exceed .85.

A rough sketch of the proposed concept is shown below in Figure 48. A single-bladed rotor is counterbalanced and rigidly attached to a drive shaft driven by a stationary electric motor, and enclosed in a safety cage. The device is mounted to a trailer that can be towed to the area that is to be insonified.

Dipole Drag Source

Similar arguments can be used if a dipole source is used instead of a thickness noise source. In this case, a paddle replaces the thick airfoil on the rotating arm, as shown in Figure 48. The paddle arm produces an in-plane drag force, which radiates harmonic noise.

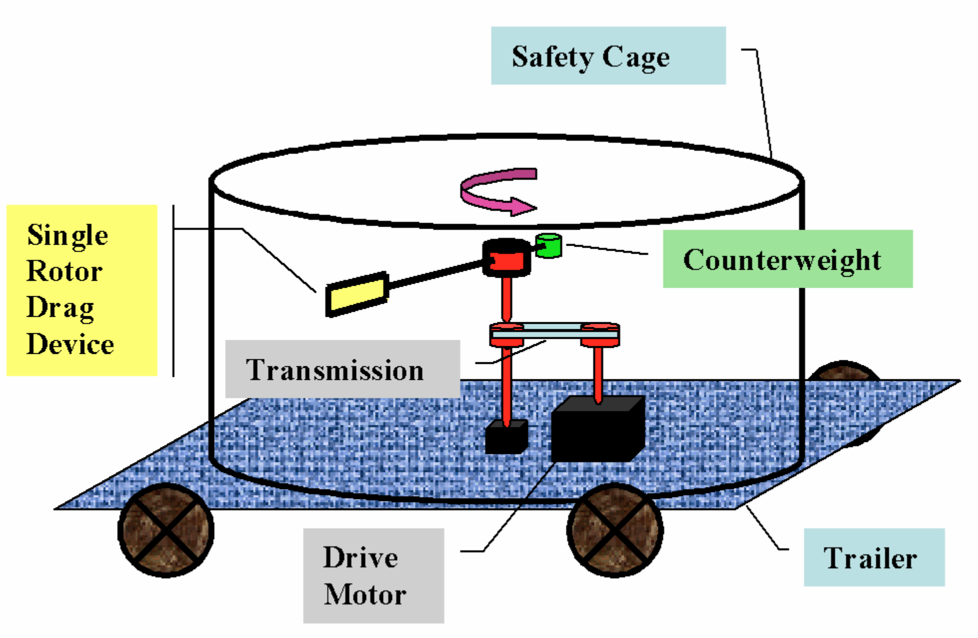

Figure 48: Conceptual Sketch of Single Blade Drag Noise Generator

Neglecting "thickness effects" of the paddle, and assuming that the drag coefficient of this device is considered to be that of a flat plate, CD = 1.0 (oriented so that the flow hits the plate at 90 degrees to surface of the flat plate), the resulting time history and harmonic character of the noise are shown in Figure 49 and Figure 50, respectively.

When compared with the pulse shapes and harmonic content of the measured and predicted sound pressure levels of the large tiltrotor aircraft described in Section 1.3, a drag dipole force yields a better approximation to the noise of the tiltrotor in the clean configuration. The harmonic level of the noise is highest at the first two harmonics and rapidly falls off with increasing harmonic number. Even the pulse shapes from this device resemble those of a large tiltrotor aircraft that is not operating in its inflow, nor creating BVI noise.

These levels have been computed on the assumption of paddle surface area of 1.5 square feet. The levels can be increased or decreased by changing the surface area. They also can be altered by changing the operating RPM, albeit while also altering the frequency content of the radiated noise. The power required to drive this device is estimated to be on the order of 50 horsepower.

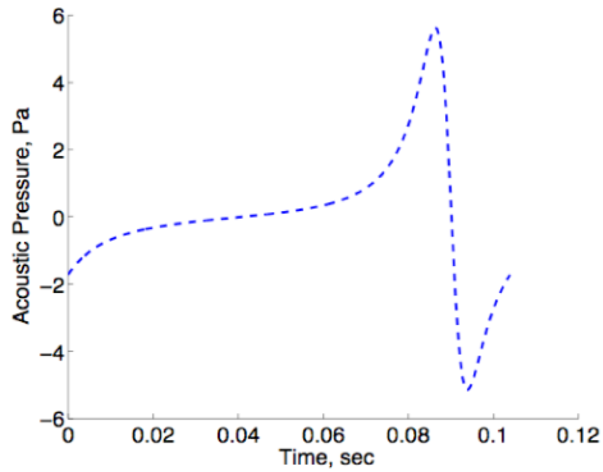

Figure 49: Time history of Noise Generated by a Rotating Dipole Drag Force

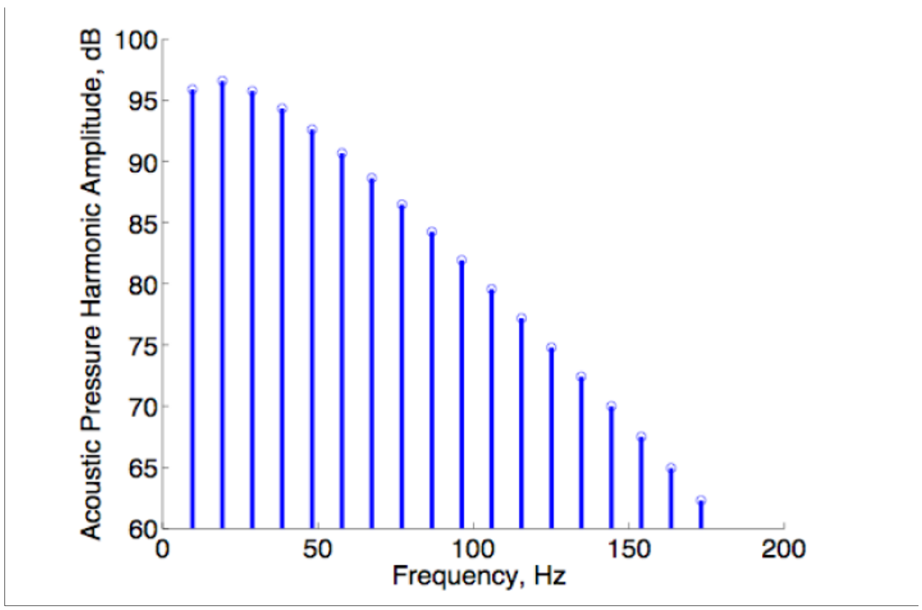

Figure 50: Harmonic Levels of Noise Generated by a Rotating Dipole Drag Force

The above calculations suggest that simulating noise of a large tiltrotor aircraft by using a single-bladed counterweighted rotating arm is theoretically feasible. Depending upon which simulated noise source is used, it is possible to roughly match the harmonic character of the radiated noise of a large tiltrotor aircraft. Further optimization and design of such a device probably would incorporate both thickness and drag effects. In this way, waveform and resulting harmonic fall-off of the large tiltrotor aircraft might be tailored to a chosen operating condition.

E. Summary

Table 7 summarizes the major advantages and disadvantages of the four devices discussed above. The first two (air modulator valves and combustion-driven sources) pose practical difficulties of operation in field settings that are not easily overcome. The two latter alternatives are more readily adaptable to reliable and affordable field operation. The siren may be the more convenient and cost-effective device to operate in the field, while the whirl stand may provide greater fidelity and flexibility in simulating tiltrotor emissions.

Table 7: Comparison of low-frequency tiltrotor noise simulation alternatives

Rotor Noise Simulation Approach	DEVELOPMENT / CONSTRUCTION		OPERATION	
	ADVANTAGES	DISADVANTAGES	ADVANTAGES	DISADVANTAGES
Electrodynamic Air Modulator & Horn	• Mature technology, low development risk • Mostly COTS hardware • Very high power levels possible	• Very large, sub-10 Hz horn must be designed and fabricated • Horn resonances and shock waves may limit controllability of harmonics and produce distortion products at high power levels	• Potentially good control over signal characteristics at moderate output levels	• Physically large • Requires extensive support equipment (generator, compressor, amplifiers, and cooling) • Potential directivity issues • Skilled operator needed to avoid overheating damage to delicate modulator valve
Combustion Noise Source (pulse jet or pulse detonation engine-type noise generator)	• Very high power levels possible	• Little COTS content. • Significant development effort required • Highly non-linear source • Large size	• Non-directional, monopole radiation for a simple pulse jet	• Non-trivial safety concerns with explosive fuel, heat generation, water cooling • Too dangerous to operate unattended • Potential reliability issues • Limited control over signal characteristics
Low-pressure, High-volume Siren Source	• Mechanically simple • Straightforward power scalability • Largely COTS hardware	• Some development needed to optimize design and control spectral content • Practical acoustic limit on the order of 1,000 acoustic watts	• Simple operation • High reliability • Non-directional radiation • Can probably operate unattended	• High power requirements will require accessory electrical generator in field use
Rotor Whirl Stand	• Mechanically low-risk – mostly COTS hardware • Similar to single-bladed rotor stand design in operation at UMD	• Special rotor blade shape fabrication • Moderate development risk • Physically large, requires on-site assembly and dis-assembly	• Simple Operation • High fidelity simulation of tiltrotor noise • Broad directivity pattern • Easily Transportable • Modest power requirements	• Requires in-plane safety cage, regular maintenance, and on-site operator

5.2.3 *Adventitious exposure study of community response near existing heliports*

Existing heliports expose nearby residents to a range of rotorcraft emissions somewhat similar to those likely to be generated by large civil tiltrotor operations.[14] However, it may be difficult to locate interviewing sites suitable for cost-effective surveying; *i.e.*, with sufficient housing densities and appropriate ranges of exposure levels and other operational parameters.

The cost and complexity of adventitious exposure field studies will be considerable, because it will probably be necessary to conduct interviews at multiple sites in different cities and/or military bases, and because per-site costs will be high. High costs are a consequence of the need to identify multiple sites (each of which will have to be qualified for inclusion in the study by site visits), and by the limited numbers of residents living near any given heliport. Further, housing conditions near otherwise-suitable sites may be atypical; cooperation of heliport operators will probably be difficult to secure; characterization of noise exposure at each site will require extensive field measurements and analyses; compilation of small sampling frames at multiple sites will be labor intensive; and confounding of helicopter noise with other community noise sources is likely. In addition, the ranges of low-frequency exposure levels and numbers of operations may not be great, complicating construction of useful dosage-response relationships.

A study of the feasibility of conducting an adventitious exposure study in the vicinity of operating heliports may nonetheless be worthwhile, if only to refine estimates of the costs and constraints.

5.3 Community annoyance of low-frequency noise of alternate rotor designs

Recent developments in rotor noise have made it reasonable to consider design measures that alter the phase spectrum of low-frequency rotor thickness noise without affecting its power spectrum (Gopalan and Schmitz, 2007, 2008). This development, in turn, raises the possibility that a tiltrotor's rotor system could be designed to minimize the direct annoyance of the vehicle's noise emissions.[15] (Fidell *et al.*, 2002 have shown that the annoyance of sounds with identical power spectra but different phase spectra can differ greatly.)

5.4 Acceptability of very-low-frequency acoustic energy in passenger cabins

In cruise mode, the interior noise environment of a large tiltrotor may include high-level pressure pulses created by rotor tips passing in close proximity to the fuselage. In vertical ascent/descent mode, and in hover and slow forward flight, cabin noise is likely to include BVI and thickness rotor noise, if not very low-frequency tones. This acoustic energy will be both

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[14] Although the levels and frequencies of infrasound produced by some light and medium helicopters partially overlap those of potential future tiltrotors, the fundamental frequencies of rotors of helicopters in common commercial use may can be an octave higher than those likely to be produced by a large civil tiltrotor; their absolute levels are lower; and the annoyance that they create may be influenced by other operational and design differences, such as BVI noise, tail rotor emissions, and noise created by tail rotor interactions with the main rotor wake.

[15] Note that altering phase relationships in blade thickness noise does not affect BVI, nor the response of structures to airborne acoustic energy. Such alterations could, however, affect the annoyance of the audible low-frequency portion of tiltrotor harmonics.

challenging and expensive to attenuate or actively cancel throughout the passenger cabin. From the passenger's perspective, such noise is also likely to be among the more characteristically annoying experiences of tiltrotor flight.

A set of laboratory studies is suggested in which duration of self-controlled exposure to very low-frequency noise serves as the measure of the acceptability of aircraft cabin noise containing varying levels and frequencies of infrasonic energy. The goal of such tests is *not* to produce conventional "annoyance ratings" (absolute category scale judgments, semantic differential scores, magnitude estimates, cross-modal matches, multidimensional scaling, or the like) which may lack directly interpretable meaning outside the data collection context, but rather, a direct behavioral indication of the amount of time such exposure is voluntarily tolerated.

The parameter space to be explored in such studies should encompass a range of expected frequencies, levels, and impulse shapes of tiltrotor cabin noise. As an initial estimate, these might range from 5 to 15 Hz, and from 110 to 135 dB. Individual pulse shapes should cover a range of BVI and thickness noise conditions for cruise and vertical operation rotor tip speeds up to Mach .85. For purposes of comparison, the cabin noise environment should include recordings of several turboprop and jet transport aircraft.

Test instructions should advise subjects that they may press a button to change simulated cabin noise environments at will. If no responses are made after several minutes, the noise should spontaneously change. The relative amounts of time voluntarily spent in cabin noise environments containing varying types and amounts of low-frequency noise would serve as a measure of the aversiveness of such exposures with respect to time spent in control (*e.g.*, conventional aircraft cabin noise) environments.

5.5 Fluctuation penalties

Moorhouse *et al*. (2007), Broner (2007), and Leventhall (2003) all believe that "throbbing" – that is, periodic - fluctuations in levels of otherwise continuous infrasonic levels exacerbate the annoyance of such exposures. The potential effects of such fluctuations on the judged annoyance of infrasonic exposure should be investigated under laboratory conditions in which levels of infrasonic pulse trains (similar to those created by tiltrotors) are systematically amplitude modulated.

The results of such laboratory judgments could help to set mitigation criteria for cabin noise; for example, by establishing whether rotor noise in the passenger compartment might be more annoying if it fluctuates around threshold levels than if it were continuously audible.

5.6 Effects of speech modulation

Yeowart and Connor (1974) report modulation of speech by very low-frequency sound at levels as low as 115 dB. If this modulation is severe enough to affect speech intelligibility, it has potential implications for both cockpit and cabin communication. Even if speech modulation does not impair comprehension of speech, it might still be highly annoying to passengers attempting to converse during tiltrotor flights.

Two laboratory studies are therefore suggested: one to determine the effect of varying degrees of low-frequency speech modulation on speech intelligibility, and one to determine the potential annoyance of such modulation. The former study could be a conventional test of the

intelligibility of phonetically balanced word lists, intended to quantify the effect on Articulation Index of varying degrees of modulation. Such a study would be conducted under both the absence and presence of masking noise. The latter study should solicit category judgments of the annoyance of connected discourse with varying degrees of speech modulation.

5.7 Audibility of tiltrotor noise in low ambient noise outdoor settings

A large civil tiltrotor in high speed cruise will be a relatively quiet aircraft, with rotor tip speeds on the order of Mach 0.5 and a fundamental blade passage rate on the order of 5 Hz. Rotor noise from such an aircraft is unlikely to be noticed in populated areas during high altitude cruise. Some of the blade passage rate harmonics might be audible in low ambient noise (low population density, outdoor recreational) and other low altitude/noise-sensitive community settings, however (*cf*. FAA, 2004; Schomer and Wagner, 1996).

Table 8 summarizes aircraft sound levels in slow forward flight with respect to ambient levels at altitudes of 500 and 2000 feet AGL. The values shown in the table cells are decibel differences by which aircraft levels exceed a bandwidth-adjusted signal-to-noise ratio corresponding to a level of audibility (d'=1.5) at which a signal is unlikely to come to the attention of an observer engaged in a foreground task other than specifically listening for noise intrusions. (Both the ambient masking noise and the human threshold of hearing are accounted for in the calculations.)

The flyover source data for the calculations are from Figure 18 (overhead at 500 feet above ground level) and Figure 20 (833 feet aft of the tiltrotor and 500 feet above ground level). Both source spectra assume slow forward flight, in which its rotors rather than its wings support the weight of the aircraft. Sound propagation to distances other than 500 feet assume a point source, inverse square spreading, and no atmospheric absorption. Because only the one-third octave bands from 40 through 100 Hz were used in the detection calculations, the numbers shown in Table 8 are probably underestimates.

The quiet ambient condition assumes no external masking. The Suburban condition is the median of the "daytime" plotting symbols found in Figure 35 on page 47, where both the signal and masker are well above threshold in all bands. The detection algorithms employed are those of Fidell *et al.* (1989).

Table 8: Tiltrotor unweighted sound pressure levels for direct overflights relative to just audible sound pressure level (in decibels) at two azimuth angles relative to the observer, under two ambient conditions.

Azimuth (degrees)	Ambient Condition	Aircraft height above ground level (feet): 500	2000
Overhead (90º)	Quiet	45	33
	Suburban	23	10
Aft (155º)	Quiet	60	48
	Suburban	37	25

The signal-to-noise ratios in this table suggest that a tiltrotor in slow forward flight would be audible in all conditions, although for the suburban condition at 2000 feet the aircraft might not be noticed until after it had passed directly overhead.

A small-scale analytic study should be conducted to estimate the potential audibility of a large civil rotorcraft in various flight configurations and in quiet outdoor conditions to clarify the potential for annoyance in such settings. If analyses suggest the likelihood that a large civil tiltrotor would be readily noticeable in low ambient noise settings, follow-on studies of the audibility and annoyance of rotor wavetrains at varying impulse repetition rates and wave shapes would be in order.

5.8 Conversion of expected tiltrotor spectra into low-frequency sound levels (LFSL)

Most criteria for evaluating community impacts of low-frequency noise and infrasound are based on information developed from small numbers of informal case studies. Such criteria are generally categorical and non-quantitative in nature, classifying sound levels not much greater than the threshold of hearing as either "acceptable" or "unacceptable". In other words, they assert little more than that infrasound loud enough to be readily audible is unacceptable, and do not clearly distinguish degrees of unacceptability.

The best-documented dosage-effect relationship between the prevalence of a consequential degree of annoyance and low-frequency sound levels is that developed from one-third octave band field measurements and large-scale social survey data at two U.S. airports (Fidell, Pearsons, Silvati and Sneddon, 2002). The predictor variable of this relationship is a single-event measure of the low-frequency sound levels that aircraft operations create several times a day in homes near runways.[16]

As a preliminary analytic means of assessing the likely magnitude of adverse community reaction to tiltrotor noise, the estimated one-third octave band sound levels noted in Section 1.2 of this report should be converted into values of the LFSL noise metric at ranges from a few hundred meters and greater from tiltrotor landing pads. Attention should also be paid to the effects of extending the lower bound of the LFSL metric, tailored to the noise emissions of large fixed wing jet transports, to frequencies below 25 Hz. Once available, such estimates would be useful for estimating the sizes of residential populations that may be consequentially affected by tiltrotor noise.

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[16] The choice of a high centile of the distribution of low-frequency sound levels created by aircraft operations, rather than a maximum, median, or any other measure of low-frequency sound levels, was predicated on social survey data to correspond with the frequency of annoyance category most often cited by respondents describing themselves as "very" or "extremely" annoyed by rattle. Use of centile-based rather than mean criteria is not unusual in accounting for reactions to vibration caused by relatively infrequent discrete events, as for example, mine blasts (Fidell, Horonjeff, Schultz, and Teffeteller, 1983) and rail-induced vibration (Zapf *et al*., 2009).

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6. APPENDIX A: LITERATURE REVIEW AND SYNTHESIS

The first two sections of this Appendix (6.1 and 6.2) review the designs and findings of individual controlled exposure laboratory studies, mostly of physiological effects and annoyance judgments. Section 6.3 reviews field studies of population-level effects observed under less-controlled but more but more naturalistic conditions.

Section 6.4 summarizes the combined findings of multiple separate studies. Section 6.5 comments on the relevance of low-frequency noise effects on ride comfort to passengers. Section 6.6 discusses the effects of secondary emissions, such as rattle, on annoyance with low-frequency noise. (Sections 4.1 and 4.2 discuss criteria for evaluating low-frequency and infrasonic noise effects, respectively.)

6.1 Reviews of laboratory studies

6.1.1 Bengtsson, Persson Waye and Kjellberg (2002)

Bengsston *et al.* paid 30 university students to set the modulation rate and relative content of low and high frequency ventilation noise in a mock office setting to be as “pleasant” as possible. When initially heard in a method of adjustment protocol, the one-third octave band centered at 31.5 Hz was amplitude modulated (to an unspecified depth) at 2 Hz to yield a “rumbling” character. The authors categorized the sensitivity of students to low-frequency noise on the basis of their self-descriptions on two absolute category response questionnaire items, but made no further mention of the effect of self-reported sensitivity on the findings of the study.

Nearly a third of the test subjects were unable to consistently gauge a preferred modulation rate, selecting low and high rates on alternate determinations. Of those subjects who had consistent preferences, seven preferred low (below 4 Hz) modulation rates, while sixteen preferred modulation rates between 8 and 10 Hz.

In the presence of amplitude modulation, preferences for high frequency content were more consistent; twenty-six of the subjects preferred ventilation noise with more high frequency content than the initial setting, while only four preferred more low-frequency content than the initial setting. In the absence of amplitude modulation, no significant differences were found in preferences for spectral balance.

6.1.2 Borredon and Nathié (1973)

Borredon and Nathié exposed 42 men between the ages of 19 and 27 to fifty minutes of a piston-driven sinusoidal tone of 130 dB at 7.5 Hz in a small pressure chamber. The volunteers were also exposed to “silence” (at an ambient level of 40 dB) and to about an octave of noise at about 200 Hz, at one-third octave band levels in excess of 100 dB. The test participants suffered no meaningful - much less clinically significant - changes in blood pressure, and no changes in a simple reaction time task that could be related to noise exposure conditions. All test participants found the noise exposure conditions tolerable. The authors noted a slight tendency to drowsiness among the volunteers.

6.1.3 Bradley (1994)

The intent of Bradley's study was procedural: to devise a method for predicting the annoyance of HVAC noise with varying amounts of low-frequency rumble and amplitude modulation. The method of adjustment study design required nine subjects to set attenuators to match the annoyance of various signals with the annoyance of a broadband reference noise that decreased in level by 5 dB/octave from a peak in the 31.5 Hz octave band. The study confirmed independent and significant contributions to annoyance judgments of both low-frequency spectral content and amplitude modulation (of 10 and 17 dB, at modulation frequencies from 0.25 to 4 Hz).

6.1.4 Broner and Leventhall (1983)

On the basis of both controlled exposure (laboratory) and case studies, Broner and Leventhall (1983) propose a set of Low-frequency Noise Rating (LFNR) spectral balance curves (see Figure 51) for avoiding annoyance and complaints in buildings due to ventilation noise-controlled background noise environments with excessive low-frequency content. The curves were intended to supplant the "NC" and "PNC" noise criterion curves originally developed by Beranek in 1957.[17]

None of the noise criterion curves developed for architectural acoustical applications offers specific design guidance for the passenger cabin of a large tiltrotor aircraft. An aircraft cabin is neither a residential nor an occupational environment, nor is it a space expected to accommodate the usual purposes for which enclosed spaces in buildings are designed.

Nonetheless, to the extent that annoyance with low-frequency noise is a component of ride comfort, and a potential sustained annoyance that might contribute to pilot workload or fatigue, the general shape of Broner and Leventhall's LFNR curves can be informative.

To avoid complaints about excessive "rumbling", Broner and Leventhall recommend that differences between noise levels in frequency regions below about 50 Hz and at frequencies an octave or two higher should not exceed 15 – 20 dB. Broner and Leventhall also caution about the annoyance of "throbbing" (that is, periodically time varying or beat frequency) background noise, and about tonal peaks at low frequencies. Given the very low frequency and relatively short duration of the fundamental rotor passage rate during hovering flight, as well as likely prominence of both tones (from rotor passage rates and harmonics) and throbbing (due to rotor phasing) in the cabin of a large tiltrotor aircraft, spectral balance may be a secondary concern in the present application.

[17] Blazier (1981) and Beranek (1989) have also published recommendations for modified NC curves extending to frequencies as low as 16 Hz. Broner (2007) views Beranek's 1989 NCB curves as far too lenient at very low frequencies.

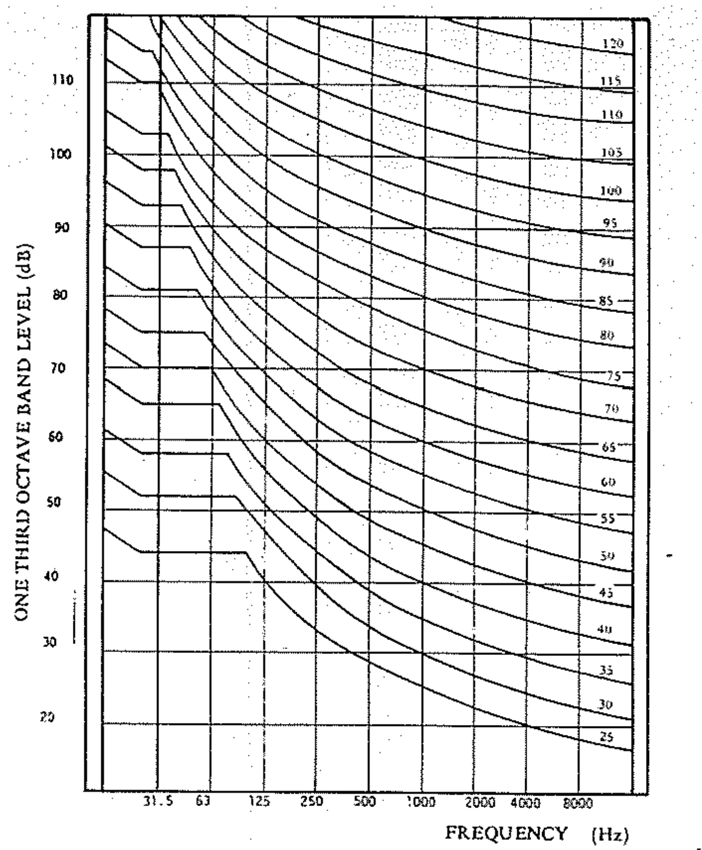

Figure 51: LFNR curves proposed by Broner and Leventhall (1983)

6.1.5 Fidell, Harris, and Sutherland (2000)

Recordings of aircraft ground noise with and without audible rattle were presented for direct paired comparison judgments of annoyance in a facility capable of accurately reproducing very low-frequency sounds. All signals were presented for judgment as they would be heard indoors, at a fixed duration of 15 seconds each. The fixed level signal was an outdoor recording of runway sideline noise made at a distance of 1,500 feet from Runway 29L at MSP (Lind, Pearsons, and Fidell, 1997), filtered to modify its spectrum to represent indoor listening conditions in an acoustically untreated residence. Intermittent rattle was digitally added in two test conditions to the indoor sideline noise test signal near its peak, at a level that did not alter the A-weighted sound pressure level of the test signal. Figure 52 summarizes the effect of adding rattling sounds to recordings of the judged annoyance of Boeing 727 and 757 aircraft.

Fidell *et al.* also found that the low-frequency content of runway sideline noise rendered it more annoying than aircraft overflight noise at comparable A-weighted sound pressure levels, and that reducing the low-frequency content of runway sideline noise proportionally reduced the judged annoyance of sideline noise.

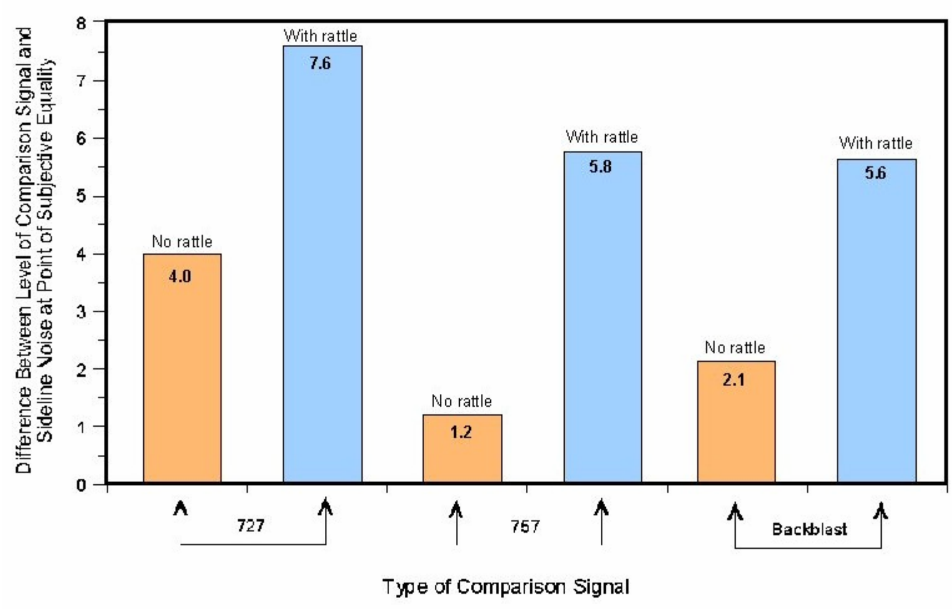

Figure 52: Difference between variable level signal and sideline noise presented with and without rattle at the point of subjective equality (mean judgments for 28 subjects, from Figure 15 of Fidell *et al.*, 2000).

6.1.6 Harris and Johnson (1978)

Harris and Johnson conducted three studies in which a total of 40 subjects were exposed to low-frequency noise and a 7 Hz tone at levels as high as 142 dB, for as long as 30 minutes. Test subjects performed serial search and complex counting tasks. No test participants reported dizziness or disorientation, and Harris and Johnson failed to observe any decrements in performance as a function of the infrasonic exposure.

6.1.7 Inukai, Nakamura and Taya (2000)

Inukai *et al.* solicited “unpleasantness” absolute judgments of pure tones at 16 one-third octave band center frequencies between 20 and 500 Hz. Thirty-nine test subjects rated the tones on a five-category scale, of which the highest two categories were “quite unpleasant” and “very unpleasant”. The instructions encouraged test participants to imagine that they were listening to the tones in residential, office, and factory settings, but no changes in the physical listening environment accompanied the various instructions. Figure 53 summarizes the findings of Inukai *et al*. (2000).

The unpleasantness ratings that the test subjects considered acceptable in the various imagined settings differed consistently from one another. It is unclear whether these differences merely reflect compliance with suggestive test instructions, nor whether the differences could be replicated in real-world settings.

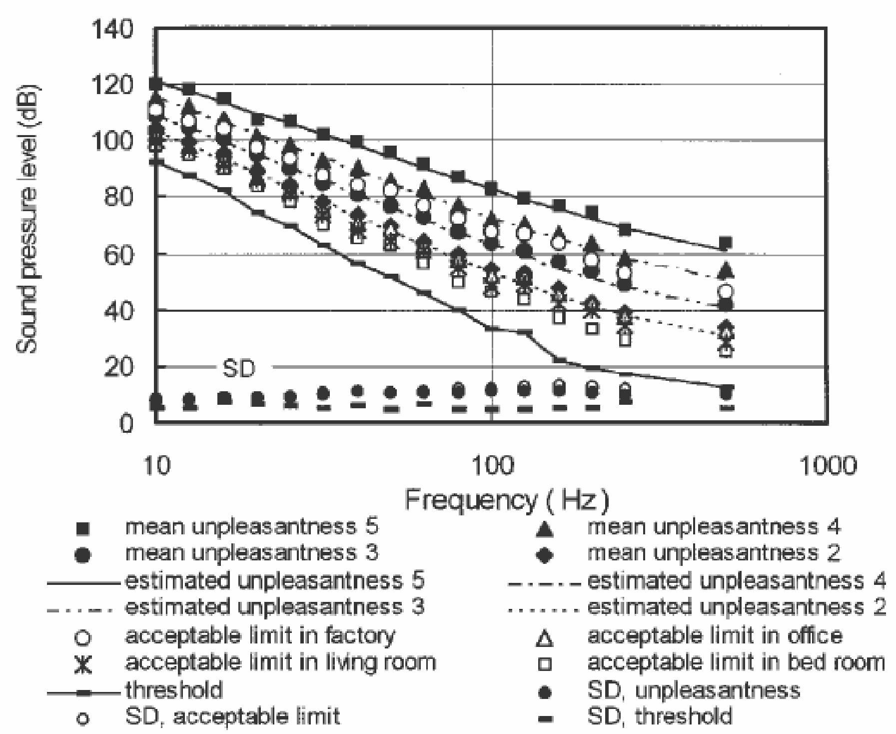

Figure 53: Equal unpleasantness contours and acceptable limits of sound pressure levels for assumed different living situations

Nonetheless, it is useful to compare Inukai *et al.*'s findings with estimates of the threshold of hearing. Figure 54 plots pure tone stimulus sound levels for two category scale findings ("unpleasant" and "very unpleasant") along with hearing threshold estimates from various sources (see section 6.4.1, page 122 for a detailed discussion of these estimates). The "unpleasant" and "very unpleasant" ratings are approximately 10 to 20 dB greater in level, respectively, than the threshold estimates between 10 and 20 Hz. The differences increase to approximately 30 and 50 dB, respectively, at 100 Hz.

6.1.8 Inukai, Taya, and Yamada (2005)

Inukai *et al.* (2005) examined the role of response bias in the apparent sensitivity of 12 listeners (all members of a Japanese "noise-sufferers society") to the audibility and annoyance of very low-frequency sounds. They concluded that the test subjects' hearing thresholds at low frequencies were not markedly different from those of other people; that test participants judged low-frequency sounds at levels not much greater than hearing thresholds as unacceptable; and that the stringency of the acceptability judgments of these test participants was greater than that of participants in other studies. The findings suggest a major role for response bias (*cf.* Green and Fidell, 1980) in judging the annoyance of low-frequency noise exposure.

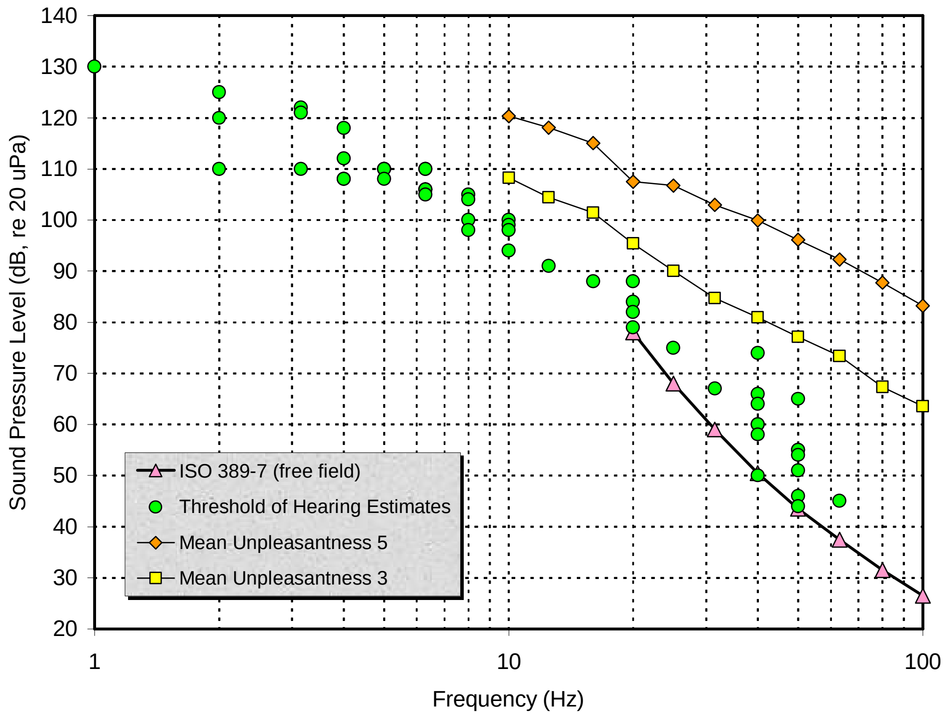

Figure 54: Comparison of Inukai et al, 2000 mean unpleasantness (3 = "unpleasant", 5 = "very unpleasant") with low-frequency hearing threshold estimates.

6.1.9 Inukai, Yamada, Ochiai, and Tokita (2004)

Inukai *et al.* measured thresholds of hearing and solicited annoyance and "acceptability" judgments from 29 test participants, of whom 9 had complained about residential low-frequency noise and the remainder were paid volunteers. Thresholds were measured adaptively at eleven discrete one-third octave band center frequencies between 10 and 100 Hz. The acceptability and annoyance judgments were solicited by the method of adjustment for imagined circumstances of "reading a newspaper quietly" and for "lying on a bed to sleep". Figure 55 summarizes the resulting judgments.

"Acceptable" and "annoying" levels of the low-frequency tones for the non-complainants vary from about 10 dB higher than absolute threshold levels at infrasonic frequencies, to about 20 dB above threshold levels at frequencies around 100 Hz. The corresponding judgments for the nine test participants who had previously complained about low-frequency noise (all members of a Japanese "Noise Sufferer Society" were at or near threshold levels at infrasonic frequencies, and only a few decibels above threshold values at higher frequencies.

The authors interpret some of their findings as generally consistent with several European criteria for acceptable residential levels of low-frequency noise. Given that all of the judgments were made under artificial conditions, with test subjects instructed to extrapolate their findings to imagined residential circumstances of exposure, it is difficult to exclude response bias as another potential explanation for the results.

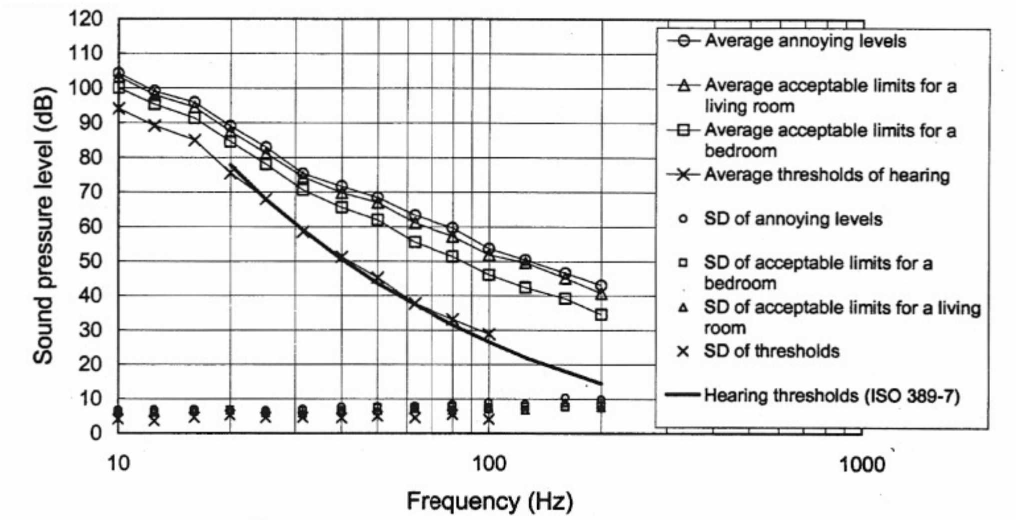

Figure 55: Summary of judgments solicited by Inukai, Yamada Ochiai And Tokita from 20 “normal” (non-complainant) test participants

6.1.10 Kelley (1987)

Kelley solicited impressions from three women and four men of simulated indoor low-frequency noise environments that were “related to the operation of wind turbines”. The informal evaluation was motivated by Kelley’s realization that residential annoyance with noise from wind turbines was not attributable directly to their noise emissions, but rather to secondary emissions inside dwellings associated with “the acoustic-mechanical response of a residential structure to acoustic loads”.

During a 45 minute test session, Kelley asked volunteers to rate the loudness, annoyance/displeasure, “sensations of vibration or pressure” and detection of “pulsations” associated with four cycles of six levels of random impulses, five levels of periodic impulses, and five more levels of random impulses. These subjective judgments correlated equally well with four variants of low-frequency weighting networks (G_1, G_2, LSPL, LSL), and with C-weighted sound pressure levels, but poorly with A-weighted sound pressure levels.

Figure 56 summarizes Kelley’s main findings, expressed in units of LSL, which are about 10 dB lower than the equivalent C-weighted levels for the tested signals. Note that “clearly unacceptable” levels are only about 10 dB greater than the “perception threshold” (presumably, the masked threshold in the 35 dB A-weighted sound pressure level ambient noise environment of the testing facility).

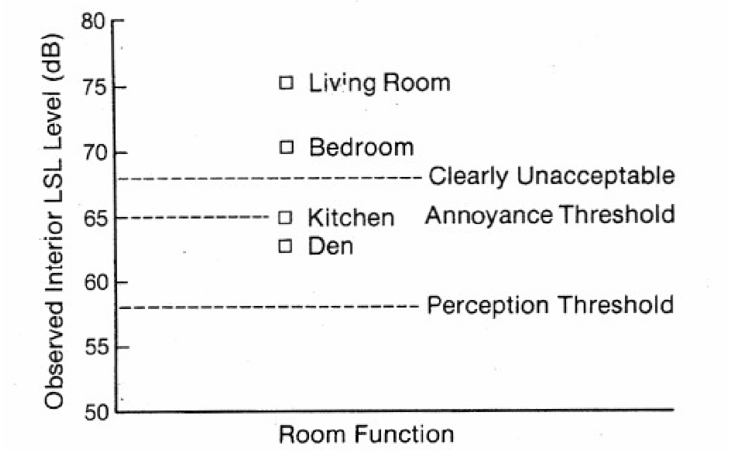

Figure 56: Summary of ratings of simulated wind turbine noise made by Kelley's 7 test participants

6.1.11 Kirk and Møller (1981)

Kirk and Møller solicited relative loudness and annoyance judgments from 15 students at frequencies from 2 to 31.5 Hz through comparisons with 63 Hz and 1 kHz reference tones. They also measured blood pressures following 20-minute exposures to 8 Hz and 16 Hz, at levels of 100, 110, and 120 dB, and solicited self-reports of annoyance and irritation, as well as sensations such as nervousness, tiredness, nausea, and dizziness.

The equal loudness contours showed the usual pattern of convergence (compression of dynamic range) at low frequencies. No effects of low-frequency sound exposures on blood pressure were observed.

6.1.12 Lydolf and Møller (1997)

In this study Lydolf and Møller conducted both equal loudness and hearing threshold evaluations. The low-frequency threshold measurements of present interest (20 – 100 Hz) were conducted in a pressure field chamber. Their chamber is shown schematically in Figure 57. The test paradigm used to determine threshold was a standardized staircase method per ISO 8253-1 (1989).

Thresholds were determined for each of 14 test subjects at eight frequencies between 20 and 100 Hz, inclusive. Frequencies tested were at one-third octave band center frequencies. Figure 58 presents the experimental results. Of interest are the open circle data points on the lowest curve. These data points range from 80 down to 30 decibels over the 20 to 100 Hz range.

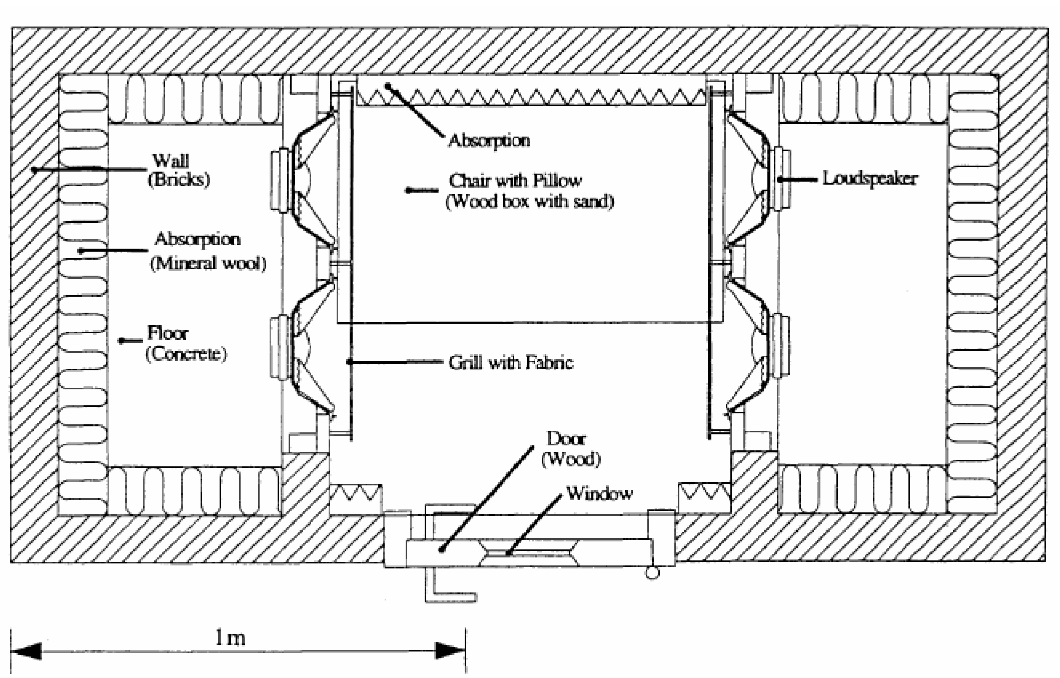

Figure 57: Plan view of Lydolf & Møller (1997) pressure field chamber used for experiments at frequencies between 20 Hz and 100 Hz. The height in the center volume was 1.40 m and in the side volumes 1.56 m.

6.1.13 Mohr, Cole, Guild, and von Gierke (1965)

This seminal report is the first well-controlled modern study of effects of very high levels of whole-body infrasonic exposure. It is also among the more detailed, clearly written and frequently cited sources of reports of potentially alarming effects, including chest wall and body cavity vibration, gagging, visual field disturbance, and prolonged post-exposure fatigue. The primary concerns in all testing were tolerability of exposure and compromises of performance. Given the motivation for testing (avoidance of adverse health effects, maintenance of crew performance during the early stages of manned rocket launches, and determining the effectiveness of hearing protective devices in mitigating auditory effects) and the relatively short durations of exposure, issues of discomfort and annoyance were of no more than secondary interest.

The authors describe 16 series of short-duration exposures to very high levels of infrasound of five noise-experienced Air Force officers. Five Air Force and NASA test facilities were employed to produce narrowband, tonal, and broadband exposures at frequencies from 3 Hz to 100 Hz, for periods of 25 seconds to two minutes. Noise effects of concern included voluntary tolerance, visual acuity, spatial orientation, fine finger dexterity, speech intelligibility, and various physiological stress symptoms and self-reports of bodily sensations.

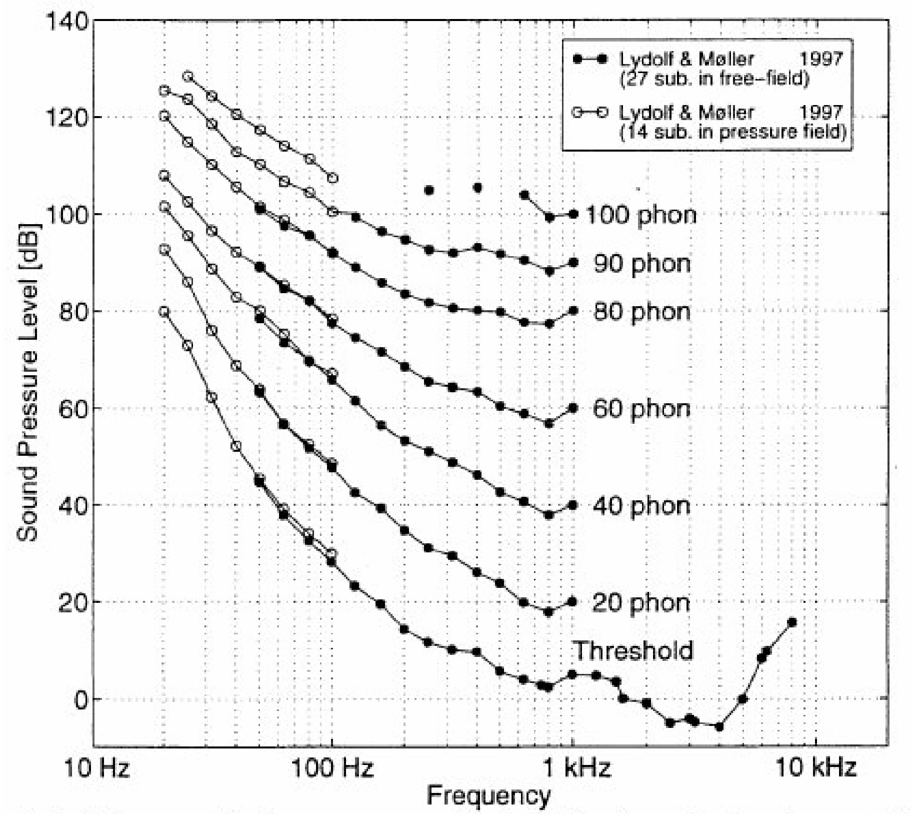

Figure 58: Preliminary results from measurements of equal-loudness level contours and the threshold of hearing (Lydolf and Møller, 1997 Figure 8)

Mohr *et al*. considered the most noteworthy responses observed during the various testing to be the non-auditory ones. At levels on the order of 150 dB in the very low infrasonic range, chest wall vibration, gagging, and changes in respiratory rhythm were regularly observed. Tonal signals at levels about 25 dB lower in the octave from 50 to 100 Hz, however, prompted reports of transient headache, choking and coughing, substernal pressure and subcostal discomfort, salivation, pain on swallowing, nausea, and cutaneous flushing, visual blurring, and fatigue. This pattern of findings suggests that it is not only fundamental rotor passage rates that may be of concern for evaluation of tiltrotor noise effects in crew and passenger compartments, but also potential effects of some of the higher rotor harmonics.

Nixon (1973) notes that in addition to the intentional exposures to infrasound of Mohr *et al*., harmonic distortion inevitably contributed additional at frequencies between 30 and 100 Hz.

6.1.14 Møller (1981)

Møller exposed sixteen volunteers on successive days to four hours of traffic noise at an A-weighted L_{eq} of 71 dB; to low level, broadband infrasound peaking at about 5 Hz at 100 dB (an exposure described as "hardly audible"); and to the same broadband infrasound at a level 20 dB greater (an exposure described as "subjectively loud"). Subjects were also exposed to a "quiet" condition of unspecified spectral composition, presumably at least 10 or 20 dB lower in level than the traffic noise exposure. Hourly blood pressure measurements were made, and a written, 7-item questionnaire was administered at the end of each daily exposure session.

Møller reports no meaningful differences in either systolic or diastolic blood pressure in any of the exposure conditions. The incidence of self-reported dizziness was significantly greater in the traffic noise condition than in quiet or either infrasound condition. No significant differences among exposure conditions were reported in tiredness, nausea, or overall fitness. The incidence of reports of headache was significantly greater in the traffic noise exposure condition than in any other, while "pressure on your ears" was greatest in the 100 dB infrasound exposure condition.

6.1.15 Møller, Henningsen and Andresen (1984)

Møller *et al.* report the findings of four studies in which test participants judged the annoyance of infrasonic pure tones. In the first experiment, 18 subjects seated in a pressure chamber drew lines whose lengths were intended to be proportional to the annoyance of tones at frequencies between 4 Hz and 31.5 Hz. The sinusoidal signals were heard for 15 minutes at levels between 75 and 114 dB. According to Møller *et al.*, the resulting "equal annoyance curves demonstrate that the lower the frequency the greater the sound pressure must be to cause a given amount of annoyance." Møller *et al.* also observed that relatively small changes in sound pressure may cause large changes in annoyance, as illustrated in Figure 59.

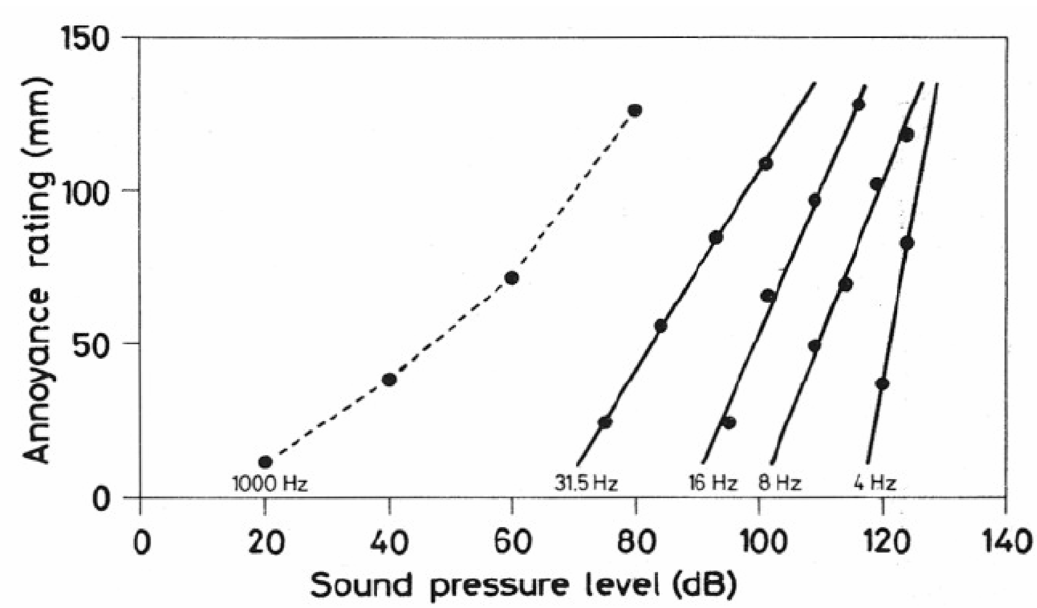

Figure 59: Growth of annoyance as a function of sound pressure level and frequency (Møller *et al.*, 1984, Figure 1)

In the second experiment, Møller *et al.* investigated the effect of exposure duration on annoyance ratings. Differences in annoyance ratings were apparent over the range of 30 seconds to 15 minutes, but they did not increase systematically with duration for all sounds.

In the third experiment, Møller *et al.* substituted one-third octave bands for pure tones. Annoyance ratings for the narrow bands of noise were very similar to those of the tones. In the final experiment, *Møller et al.* mixed an octave band of pink noise centered at 1 kHz with a tone

at 16 Hz. Although the total annoyance of the composite signal was found to be more annoying than that of the infrasound alone, the pattern of findings did not support the hypothesis that a sound with an "unbalanced" spectrum (that is, one with considerable low-frequency content) is more annoying than a sound of similar level but less prominent low-frequency content.

6.1.16 Moorhouse, Waddington and Adams (2007)

Moorhouse *et al.* asked 18 test subjects to adjust the level of a set of recorded and synthesized sounds to "acceptable" levels. Three older subjects described themselves as disturbed by low-frequency sounds. Another 8 subjects between the ages of 55 and 70 years were selected for their lack of low-frequency noise complaints. The remaining 7 subjects were "from a younger age group". All were instructed to "Imagine you are at home during the day" and to "Imagine that you are home at night and trying to get to sleep", and to press a button at any time during three listening sessions of 20 minutes' duration when sounds were "not acceptable to live with."

The test sounds differed in part in their degree of temporal fluctuation. Little description is provided of the nature (spectral content, depth and rate of amplitude modulation) of five "real" sounds, other than that they were recorded in the homes of complainants and processed by concatenating ten second samples into "homogeneous" recordings lasting three minutes. The synthetic sounds were formed by beating tones at 40 and 60 Hz with tones 1.5 Hz higher in frequency. No explicit information is provided about the initial presentation levels, nor the audibility of the test sounds in the testing environment.

The average equivalent (presumably A-weighted) sound pressure level at which the subjects judged the sound with the least temporal fluctuation "acceptable" for imagined nighttime home exposure was about 70 dB. The four recorded sounds with greater temporal fluctuation were judged acceptable at night at equivalent levels about 5 dB lower. Although no comparable explicit information is provided about the acceptability of imagined daytime home exposure, the authors assert that "[acceptable] daytime levels were set an average of 3 – 4 dB higher than the corresponding night time levels." No indication is provided about the likelihood that any of the observed differences could have arisen by chance alone, nor do the authors discuss the potential contributions of response or instruction bias to their findings.

Noise levels judged "acceptable to live with" by the three test subjects who had complained about low-frequency noise in their homes were about 2 to 4 dB *higher* in absolute level than the noise levels judged acceptable by the 15 non-complainants. However, the (unreported) hearing thresholds of the three complainants were assertedly higher than those of other subjects. The authors thus concluded that "in relative terms", low-frequency noise "sufferers tend to set the threshold of acceptability much closer to the threshold of hearing than other groups." Despite differences in the acceptability ratings of the three noise sufferers, the authors nonetheless conclude that low-frequency noise complaints are not the product of exceptional hearing sensitivity.

Moorhouse *et al*. also conclude that sound with $L_{10} - L_{90}$ differences greater than 5 dB at modulation rates greater than 10 dB/s merit a 5 dB "fluctuation penalty", whether during daytime or nighttime hours.

6.1.17 Mortensen and Poulsen (2001)

Mortensen and Poulsen solicited written annoyance ratings from eighteen test participants of seven "low-frequency test signals" of two minutes' duration. The sounds were presented twice, in random order, at A-weighted pressure levels of 20, 27.5, and 35 dB. The "preliminary" analysis contained in this nominally peer-reviewed article consist solely of two charts which suggest that mean annoyance ratings increase with presentation level, and that annoyance ratings for supposed "day-evening" and "night" conditions differ. No spectral information is provided from which the low-frequency content of the test signals can be estimated.

6.1.18 Mueller and Mayes (1967)

Over a period of three days, Mueller and Mayes subjected eight squirrel monkeys to a total of 12 hours of 140 dB sinusoidal sound pressure levels at 2 Hz. Apart from observing that some of the monkeys slept through the exposure, the reference contains no information about any other consequences of the infrasonic exposure.

6.1.19 Nakamura and Inukai (1998)

Nakamura and Inukai instructed fifteen test subjects to judge various bodily sensations (including pressure and vibration in the chest, ear, head, abdomen, buttock, and leg), as well as feelings of discomfort, "oppression", suffocation, heartbeat, and sound quality (noisiness, loudness, total intensity, and "muddiness") while they were exposed to various combinations of sinusoidal signals at frequencies from 5 to 40 Hz and at sound levels between 70 and 110 dB.

A factor analysis of the subjects' ratings identified three factors that discriminated reasonably well among reports of auditory, vibration, and pressure variables. The factors were not mutually orthogonal however, and did not resolve complex interactions among frequency, sound pressure level, and both sound quality and magnitude of discomfort.

6.1.20 Nakamura and Tokita (1981)

After exposing 30 students and housewives to 20 s long sinusoids of frequencies between 2 and 100 Hz and at levels between 50 and 120 dB, Nakamura and Tokita asked them fill out questionnaires inquiring whether they had heard the sounds, felt annoyed or displeased with them, had an "oppressive feeling", or felt a vibration. The authors state that some subjects reported "feelings of oppression and vibration", and noted considerable individual differences in responses.

6.1.21 Persson Waye, Bengtsson, Kjellberg, and Benton (2001)

Persson Waye *et al*. report a small decrease in performance in one of four cognitive tasks (a proof reading task) in a group of 32 test subjects exposed to relatively low levels (70 dB or less in one-third octave bands in the vicinity of 40 Hz) of low-frequency noise, relative to the performance of group of subjects exposed to noise of the same A-weighted sound pressure level (40 dB) without the additional low-frequency content (see Figure 60). Both the "low-frequency" and "reference" background noise environments were broadband rather than tonal, but the noise in the 31.5 Hz band of both was amplitude modulated at 2 Hz.

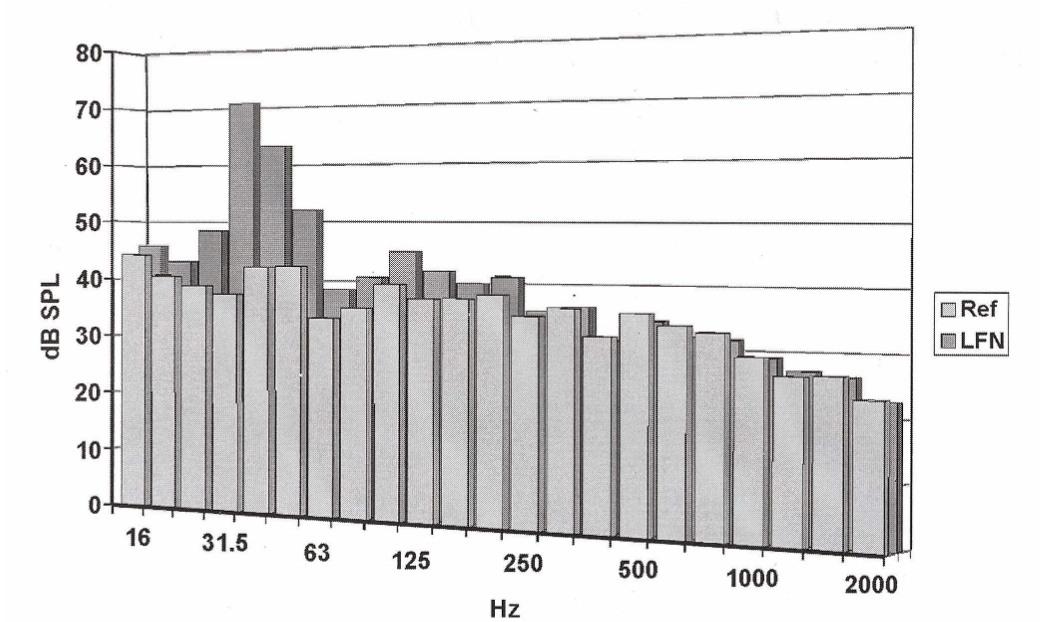

Figure 60: One-third octave band sound pressure levels of the reference noise and the low-frequency noise (dark colored bars) used during the test sessions, measured at the position of the subject's head (from Persson Waye *et al.*, 2001, Figure 1).

Neither the depth nor percent of modulation was specified, but the net effect was probably sufficient to produce a noticeable throbbing character in the higher-level "low-frequency" background noise condition. Given that the absolute threshold of hearing at 31.5 Hz is on the order of 70 dB, it is unlikely that either the broadband energy or the modulation was audible in the reference ("flat" background spectrum) condition.

6.1.22 Slarve and Johnson (1975)

The authors exposed four college-age men to infrasound at discrete frequencies between 1 Hz and 30 Hz at levels as high as 144 dB for periods as long as eight minutes. These exposures were the first whole-body studies in the Air Force's dynamic pressure chamber (see Figure 6) since Mohr *et al.*'s (1965) studies in other facilities had established that exposures to levels in excess of 150 dB were not voluntarily tolerated even for periods as short as 2 minutes.

Otoscopic examinations and pre- and post-exposure audiograms were administered, while respiration and heart rate were monitored continuously during exposure. Self-reports of sensations experienced during exposure were made twice per session. Pressure buildup in the ears was the most consistent finding at all frequencies at levels between 120 and 126 dB, but no adverse physiological consequences of any of the experimental exposures were noted.

Since the test subjects were not asked to make judgments about annoyance, "acceptability", "displeasure", or any other attitudes toward the exposure, the absence of adverse physiological consequences cannot be interpreted as demonstrating that tonal exposures to high levels of infrasound are comfortable or appropriate in the cabin of a civil tiltrotor aircraft.

6.1.23 Tokita and Nakamura (1981)

In this study the authors review window rattle and the subjective response to rattle-free low-frequency noise. They propose frequency weightings relating to each of the phenomena.

In their first experiment, designed to determine the onset of window rattle as a function of frequency, the authors subjected several different window fixtures to pure tone excitation in a laboratory test facility. Figure 61 shows the results of their experiment. Minimum required excitation sound pressure level is shown on the ordinate, and excitation frequency on the abscissa. They provide a curved, dashed line indicating the lower bound of their data (which has a nominal 10 decibel range at almost all frequencies). From this figure the authors conclude a reasonable sensitivity offset slope to be 12 dB per octave for frequencies above 10 Hz. The justification for the 10 Hz lower bound is not clear. The data appear to suggest a lower bound of 20 Hz as more appropriate since there seems to be little dependency on frequency below this value. Furthermore, the horizontal dashed line for frequencies below 10 Hz is 10 decibels lower than the lowest rattle onset sound pressure level measured. Nonetheless, the figure confirms other structural response studies that demonstrate maximum structural sensitivity in the 10 to 20 Hz range, and hence the range of greatest concern regarding rattle-induced annoyance.

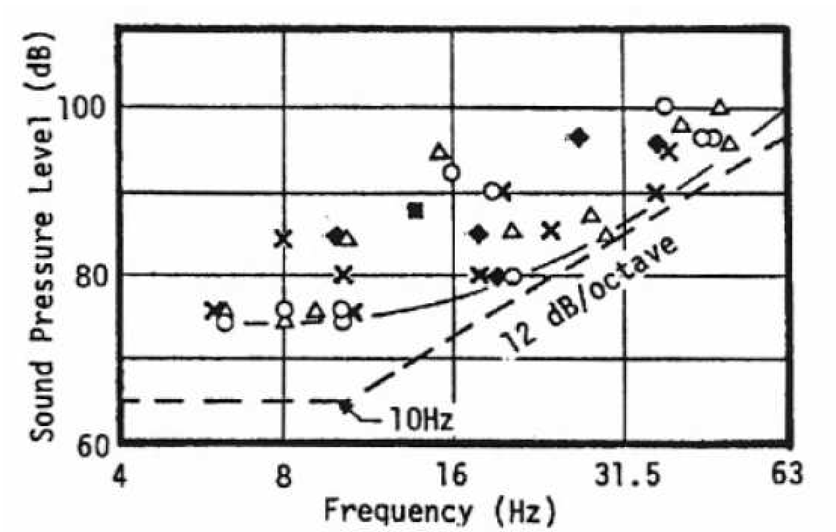

Figure 61: Minimum sound pressure level for window rattling (Tokita & Nakamura, 1981, Fig. 1).

In their second experiment the authors examine “feelings of oppression and vibration” in a rattle-free laboratory setting. Using an unspecified number of test subjects, the authors sought out the frequency of maximum human sensitivity to the above-stated subjective criterion. They conclude the frequency of maximum sensitivity to be 50 Hz, with sensitivity dropping at –12 dB/octave below this frequency and –18 dB/octave above. Consequently, they conclude the LSL curve (shown in Figure 27 on page 42) to be the most appropriate frequency weighting function for subjective response to low-frequency noise absent rattle.

6.1.24 Tokita, Oda and Shimizu (1984)

Tokita *et al*. solicited judgments of noisiness, annoyance, displeasure, and "vibratory" and "oppressive" feelings from 30 subjects of five sets of noises heard at seven levels each. The noises were band limited samples of various recorded (non-aircraft) sources, with peaks between 10 and 125 Hz. Correlations between the subjective judgments on all of the rating scales and six frequency-weighted metrics (including A-weighting!) were all high, and with a few possible exceptions, probably not significantly different from one another.

Tokita *et al*. nonetheless argue on the basis of both the present findings and of prior Japanese studies for a "LSL" (low-frequency sound level) weighting in preference to the G-weighting that was subsequently adopted by ISO 7196:1995.

6.1.25 Yamada, Watanabe, Kosaka, Uchiyama, Kasada, and Tamura (1984)

After recounting several cases of complaints about low-frequency noise, Yamada *et al.* describe electrophysiological measurements (Galvanic skin response, respiration rate, heart rate, and EEG) made in a low-frequency test chamber on nine students and twelve complainants. The test subjects were exposed both to rattling noises and to unspecified signals at frequencies between 16 and 125 Hz, at levels between 60 and 100 dB.

Not surprisingly, no systematic interpretations of the measurements were possible. Transient changes in GSR were observed in some subjects at the onset of some sounds, but other changes in GSR bore no obvious relationship to noise exposures. Some subjects showed increases, but others (mostly students rather than complainants) decreases in respiration rate at various sound levels. Heart rates of university students were unaffected by low-frequency noise exposure, but some of the complainants' heart rates increased. No consistent changes in EEG were apparent as a function of noise exposure.

6.1.26 Yamazaki and Tokita (1984)

Twelve male students sleeping in a two laboratory test chambers were exposed to tonal signals at 10, 20 and 40 Hz at levels ranging from 55 to 104 dB while wired for EEG and EOG recordings. The authors present no systematic account of the analysis of the measurements, but note that it was "difficult to determine the change of sleep stage after the exposure".

Despite the near-complete absence of any quantitative analysis, the authors conclude that the influence of the low-frequency exposure may be evident only at audible sound levels; that the deeper the sleep stage, the less apparent any effects are; and that sound levels of about 100 dB at 10 Hz, 90 dB at 20 Hz, and 65 dB at 40 Hz are required to observe any effects on Stage I sleep.

6.2 Summary of specific reported effects

Table 10 and Table 11 in Appendix B summarize reports of physiological and health/safety effects of infrasonic exposure, and of cognitive and other effects, respectively. The frequencies and levels cited in the table should all be viewed as approximate, given the many difficulties of controlling and reliably measuring infrasound in the laboratory, not to mention the small numbers of studies and test subjects, as well as the subjective nature of some of the effects and the inherent variability of human response to noise.

It should also be noted that few of the tabled findings have been widely replicated, and that some efforts to replicate reported findings have been unsuccessful. For current purposes (general

design guidance and identification of frequency/level regions of further research interest), however, failures to replicate results are of lesser importance than reports of positive findings.

6.2.1 Aural pain

von Gierke and Nixon (1976) estimate the threshold of pain at low infrasonic frequencies (at or below 5 Hz) at about 160 dB. The pain threshold decreases to about 140 dB in the vicinity of 20 Hz; into the high-130 dB range by about 50 Hz; and to levels as low as 120 – 130 dB at the mid-range frequencies of greatest hearing sensitivity.

6.2.2 Temporary threshold shift

Alford *et al.* (1966) and Jerger *et al*. (1966) report modest (10 – 20 dB) temporary threshold shifts in some test subjects following three minute exposures to infrasound in the range of 2 to 12 Hz at levels as high as 140 dB. Other researchers (including Nixon, 1973, and Johnson, 1982) have also reported similar findings in some test subjects following somewhat longer duration exposures.

The shifts were apparent at much higher frequencies, but generally recovered quickly. It is possible that the reported shifts were due at least in part to a loss of conductive efficiency of sound transmission across the tympanic membrane (through loss of pressurization of the middle ear), rather than to any impairment of sensorineural function.

Other studies (*e.g., Mohr et al*., 1965; Slarve *et al*., 1975), however, have failed to observe TTS in some test subjects following exposures of varying durations and intensities to very low-frequency sounds.

6.2.3 Fullness/pressure in the ears

The literature contains multiple reports of sensations of pressure (Karpova *et al*., 1970; Nixon and Johnson, 1973), fullness or even tickle (Mohr *et al*., 1965), in the ears at very low frequencies, at infrasonic levels as low as 127 to 133 dB (Broner, 1978). Møller and Pedersen (2004) suggest that such sensations occur at levels about 20 to 25 dB higher than absolute thresholds of hearing sensitivity.

The common conjecture about the underlying physiological mechanism is that high levels of very low-frequency airborne acoustic energy in the external meatus force the tympanic membrane to pump air out of the Eustachian tube, which, when collapsed, does not permit equalization of air pressure in the middle ear.

The sensation of fullness persists even after the infrasound ceases, for periods of half an hour or longer, until jaw movements or intentional re-pressurization of the middle ear (via the Valsalva maneuver[18]) permit equalization of pressure on both sides of the eardrum.

[18] The Valsalva maneuver is performed by attempting to forcibly exhale while keeping the mouth and nose closed.

6.2.4 Chest wall vibration[19]

Ollerhead (1968) and Leventhall and Kyriakides (1974) have made direct measurements of the relationship between received sound level at the body and vibration of the chest walls of eight people due to low-frequency sound excitation, These data are reproduced in Figure 62. The data from Ollerhead (1968) are averages for two male subjects. The individual vibration response curves for the six subjects of Leventhall and Kyriakides (1974) were obtained from their Figure 90. The overall average and one standard deviation for the combined data set are shown in Figure 63.

These data represent the vibro-acoustic transfer function measured on the chest wall as a function of frequency. This transfer function characterizes the vibration response of the chest wall in units of g relative to the acoustic pressure on the subject's chest wall in units of μPa. The transfer function is expressed in decibels re 1 μg / 20 μPa, where 1 μg is a standard reference acceleration of 1 millionth of a "g," and 20 μPa is the customary reference pressure for sound levels.

An estimate of the expected threshold of detection of chest wall vibration due to low-frequency excitation at the feet of standing individuals can be derived in the following manner. First, the vibration detection threshold at the feet of people exposed to vertical or horizontal mechanical vibration is derived from two ISO standards (ISO, 1985 and 1989a). This threshold, expressed as the acceleration level in decibels re 1 μg, is shown by the solid line of Figure 64. Second, measurements of the decay in vibration through the body from the feet to the chest for mechanical vibration of a standing subject (Goldman and von Gierke, 1969) may be applied to estimate the threshold of detection of such vibration at the chest of a person. The estimated range is represented by the shaded area in Figure 64.

Third, the low-frequency sound levels expected to cause the detectable vibration levels of the chest shown in Figure 64 can be estimated by combining the latter estimated threshold for detection of chest vibration with the average vibro-acoustic response data in Figure 63. This estimate is shown by the shaded area in Figure 65. The range of the estimated chest threshold reflects the one standard deviation range of the chest wall vibro-acoustic response data shown earlier in Figure 63, and the range for detection of chest vibration shown in Figure 64.

Perspective on these estimates of chest wall vibration may be gained by comparing them with direct measurements of responses of people exposed to low-frequency sound fields, as described by Nakamura and Tokita (1981). The additional solid lines in Figure 64 replot the Nakamura and Tokita data to show differing levels of subjective response to low-frequency acoustic energy. The results of the estimation process described in the preceding paragraphs are generally consistent with their findings of just detectable signal levels, agreeing particularly well below 40 Hz. Nakamura and Tokita included the equal loudness level contour in their graphic to demonstrate that the slope of their detection and "annoyance" observations are also consistent with subjective loudness, especially below 40 Hz, as would be expected at low detetability sound levels.

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[19] The information presented in this sub-section, paraphrased from the final report of the Richfield-MAC Low-frequency Noise Expert Panel (Fidell *et al*., 2000), was originally prepared by Louis Sutherland.

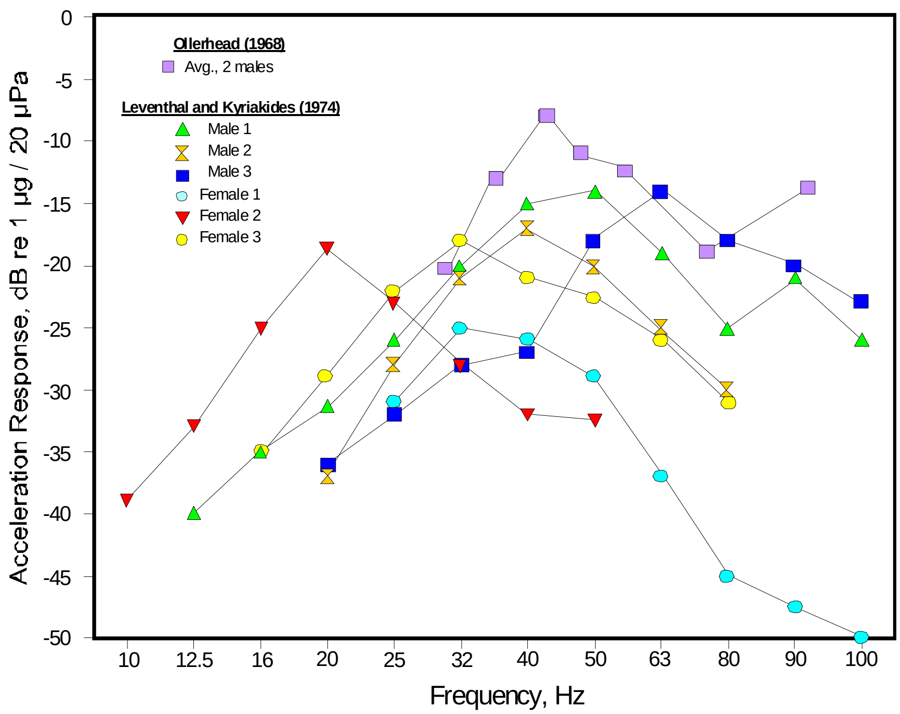

Figure 62: Vibration response of chest wall to acoustic excitation measured on 5 male and 3 female subjects (Ollerhead, 1968; Leventhall and Kyriakides, 1974).

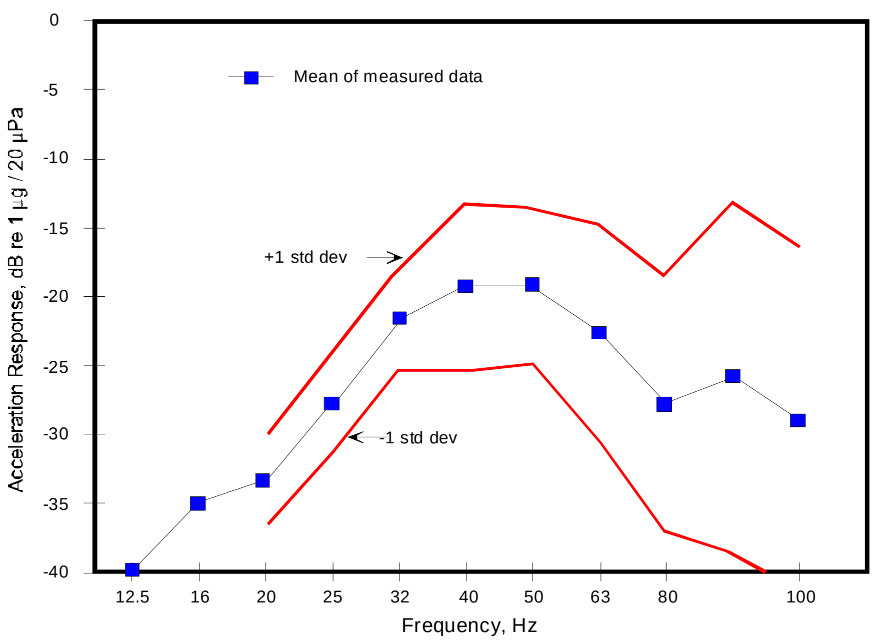

Figure 63: Mean of vibration response to acoustic excitation of chest wall for data of Figure 64. Upper and lower curves show ±1 standard deviation (Fidell *et al.*, 2000, Figure 91).

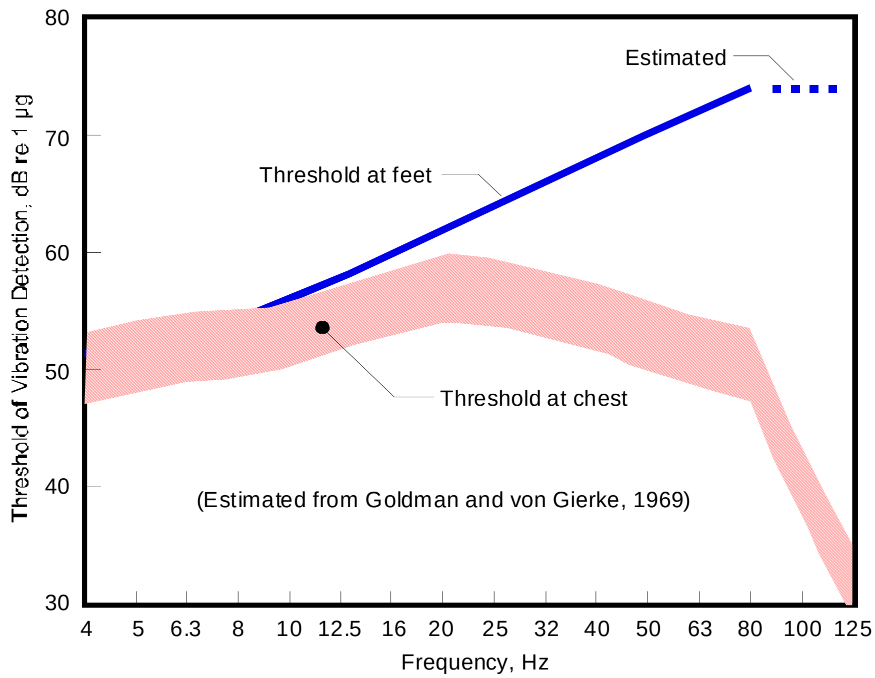

Figure 64: Vibration detection thresholds at the feet and the chest for people based on ISO standards for vibration at the feet (ISO, 1985, 1989) and measured vibration attenuation from foot to chest (Goldman and von Gierke, 1969, Figure 1)

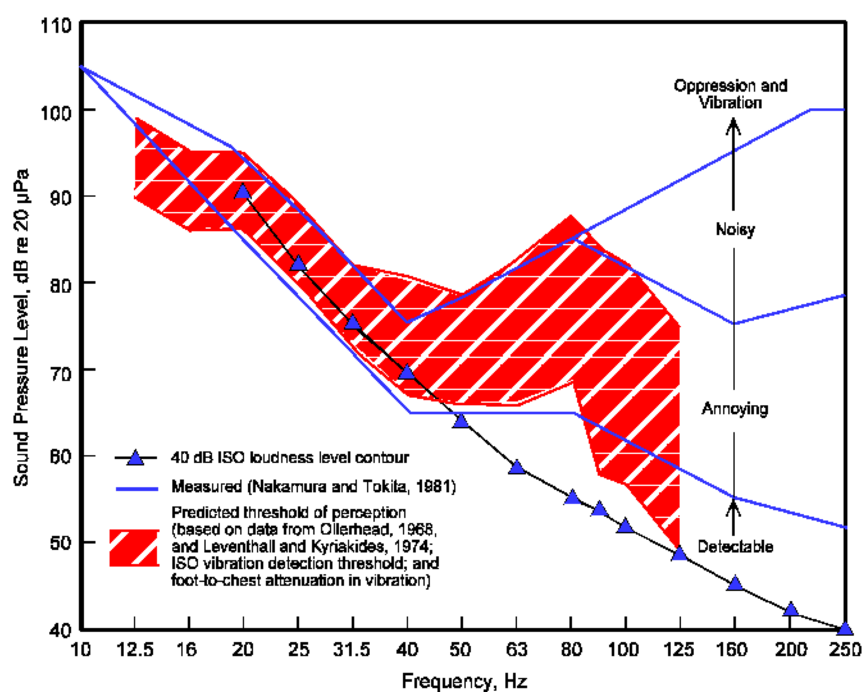

Figure 65: Comparison of predicted threshold for acoustically-induced vibration of the chest based on the preceding two figures and directly measured subjective responses to low-frequency acoustic excitation for 54 subjects (reproduced from Fidell, *et al*, 2000 Figure 93)

6.2.5 Audibility of low-frequency and repetitive impulsive sounds

Heavy lift rotorcraft will overfly not only urban areas, but also areas of low population density, including rural, park and wilderness public lands managed for outdoor recreational purposes. Since Congress has declared via Public Law 100-91 its intent to protect and preserve natural quiet, the audibility of low-frequency noise created by heavy lift rotorcraft is of potential concern in such settings, even though the aircraft is expected to be fairly quiet in cruise configuration.

Figure 66 through Figure 68 shows unpublished findings of laboratory studies conducted by the senior authors of this report for the U.S. Army Research Office over a range of repetition rates of 5 Hz to 40 Hz, corresponding to the range of fundamental and harmonics of blade passage rates of present interest. In these controlled listening tests, participants determined when impulse wave trains of varying repetition rate and observation interval durations were just audible in band limited white Gaussian noise. Each impulse was a single 1000 Hz sinusoid in a train lasting from 0.25 to 2.00 seconds. To provide a convenient point of reference test participants also listened for a single impulse randomly placed in a 500 ms observation interval.

Figure 66 plots the growth of energy required to maintain constant detection performance for six impulse repetition rates of 5, 10, 13, 20, 30, and 40 Hz on the abscissa. The ordinate shows the shows the normalized signal energy-to-noise power density ratio between the wavetrain and a single impulse from the wavetrain. The data points for differing observation intervals are plotted separately and least squares linear regression lines shown for each family of points.

The slopes for the various observation intervals shown in Figure 66 are not significantly different from one another. Furthermore, they are not significantly different from 1.5 dB per doubling of impulse repetition rate. This finding suggests that (at least for observation intervals greater than 250 milliseconds) people act as statistical integrators of signal energy. That is, instead of integrating the total energy of all impulses, they perform as if orthogonally summing the detectabilities of each individual impulse. This finding is consistent with prior studies which show that human observers effectively act as energy integrators up to 250 to 300 milliseconds, and thereafter perform as if they listen in a succession of these shorter intervals and statistically sum the short-duration detection outcomes (resulting in the 1.5 dB per doubling slope).

To gain further insight into the contributions of both repetition rate and observation interval duration, and to confirm the statistical integration performance model, Figure 67 replots the data points shown in Figure 66 to show the growth of energy required to maintain constant detection performance with increasing numbers of impulses in the observation interval (*i.e.* the impulse repetition rate multiplied by the observation interval duration). Families of data points for differing observation intervals are plotted separately.

Like Figure 66, the slopes for the various observation intervals shown in Figure 67 are very nearly the same, and not significantly different from one another. Furthermore, they are also not significantly different from 1.5 dB per doubling of observation interval duration. This finding confirms the validity of the statistical integration model for predicting detection performance. Had the observers been able to perform as ideal energy integrators, the regression lines in both the foregoing figures would have had zero slopes. The positive slope observation demonstrates

observers operate with less efficiency than a pure energy detectors, but with an efficiency consistent with statistical integration of individual impulses.

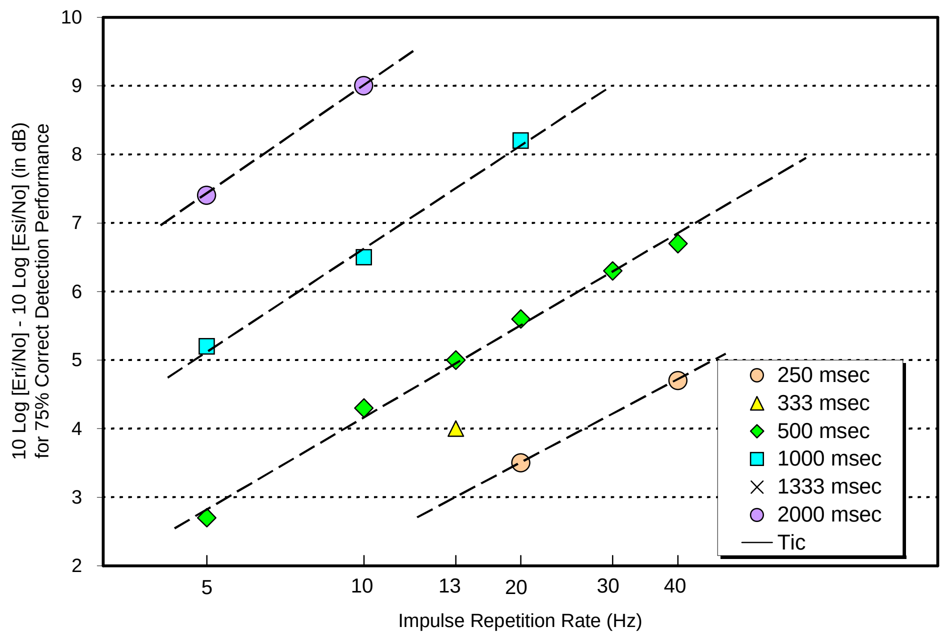

Figure 66: Observed relationship between signal energy required for detection and impulse repetition rate for observation intervals ranging from 250 to 2000 milliseconds.

Figure 67 also provides the foundation for another important inference: that a linear relationship exists between the energy required for the detection of a single impulse (the red triangle in the lower left portion of the graph) and the other data points. Beginning with the 250 ms data points, the single impulse data point falls on the same nominal 1.5 dB/doubling line as that passing through the two 250 ms data points. This shows that the 250 ms data point E/N_0 values may be predicted from the single impulse. Further, the relationship between the vertical offsets between the linear clusters of data points for the 250 ms and other observation intervals shows that all may be predicted from the single impulse given knowledge of the repetition rate and observation interval.

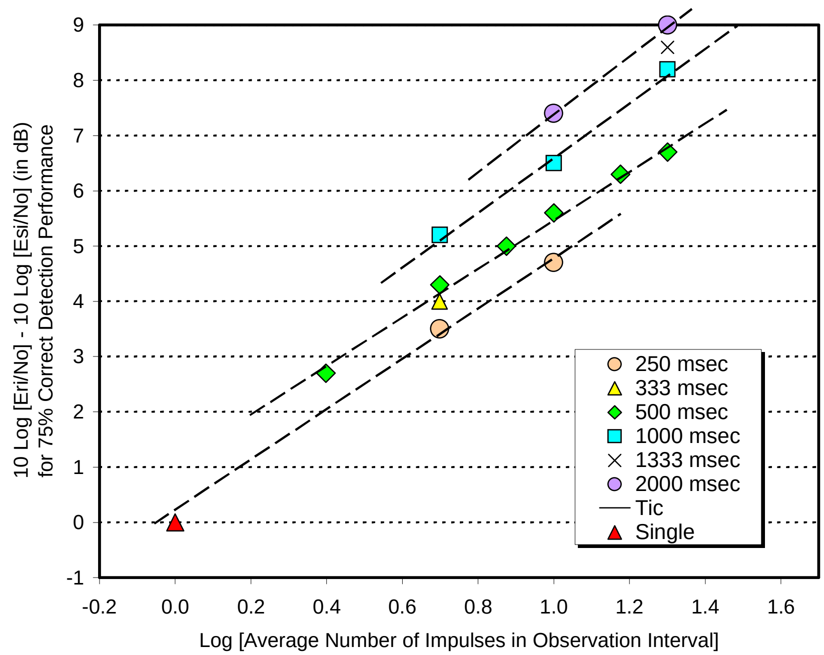

Figure 67: observed relationship between signal energy required for detection and number of presented impulses during observation interval (250 to 2000 millisecond durations).

The least square fits to each set of data points in Figure 67 show orderly relationships between the energy to noise ratio, repetition rate and observation interval duration. Their positive slopes of about 1.5 dB per doubling of repetition rate (or 5 dB/decade) indicate that greater signal energy is needed at increasing repetition rates to maintain constant detection performance, and that these slopes are effectively independent of observation interval durations. Hence, the equation for each line may be described as shown in Equation 5.

$$10 \log_{10}(E_{ri} / N_0) - 10 \log_{10}(E_{si} / N_0) = 5 \log_{10}(RR) + K_j$$

Equation 5

where:

E_{ri} / N_0	= signal energy to noise power density ratio of impulse wave train
E_{si} / N_0	= signal energy to noise power density ratio of a single impulse
RR	= impulse repetition rate (Hz)
K_j	= a constant that positions the j^{th} regression line vertically on the graph

The data of Figure 66 and Figure 67 may be collapsed across observation interval. Figure 68 plots impulse repetition rate on the abscissa, but the ordinate plots the same signal energy-to-noise power density ratio minus an empirically-derived observation interval adjustment, 8 log10 (D).

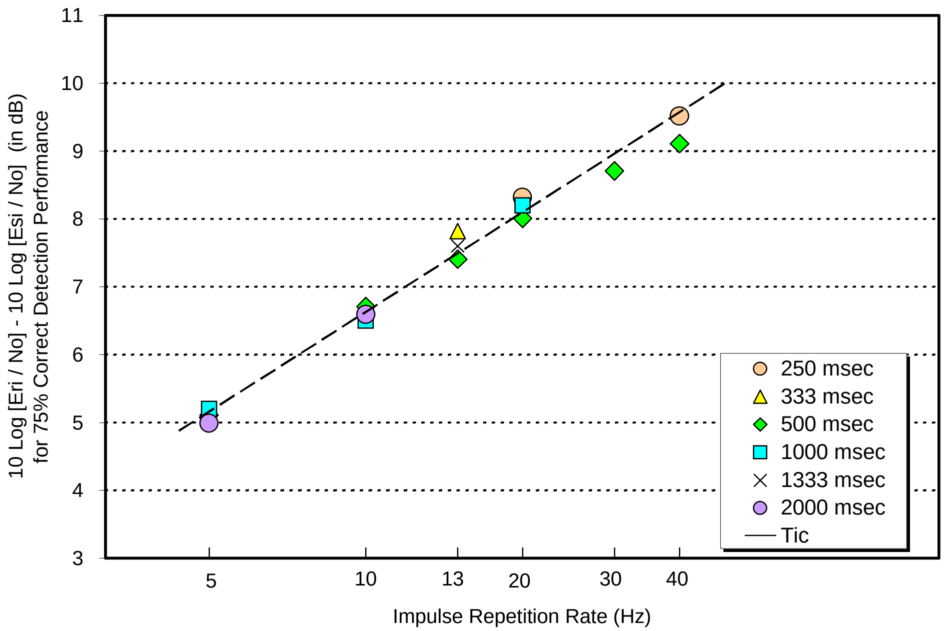

Figure 68: Observed relative signal-to-noise ratios ($10 \log_{10} [E_{ri} / N_0] - 10 \log_{10} [E_{si} / N_0]$) of equally detectable impulse wavetrains as a function of impulse repetition rate collapsed over observation interval duration by $8 \log_{10} (D)$.

The line through the data points is a least squares fit for a slope of 5 dB per decade of repetition rate (1.5 dB per doubling). The tight fit of the data points about the line (± 0.3 dB) suggests a strong predictive relationship of energy-to-noise power density ratio needed for detection as a function of just two parameters: repetition rate and observation interval.

Equation 6 describes this line. The detectability of the single impulse can be well predicted using the methods of Horonjeff (1983) and Fidell (1989).

$$10 \log_{10} (E_{ri} / N_0) - 10 \log_{10} (E_{s\,i} / N_0) = 5 \log_{10} (RR) + 8 \log_{10} (D) + 1.5$$

Equation 6

Rearranging terms, the equation may be rewritten in a predictive form as:

$$10 \log_{10} (E_{ri} / N_0) = 10 \log_{10} (E_{s\,i} / N_0) + 5 \log_{10} (RR) + 8 \log_{10} (D) + 1.5$$

Equation 7

Equation 7 states that the signal energy needed for wavetrain detection as a function of a single impulse in the train, repetition rate, and observation interval duration. Since the detectability of the single impulse can be well predicted using the methods of Horonjeff and Fidell (1983) and Fidell *et al.* (1989), the incorporation of the repetition rate and interval duration terms yield the energy to noise ratio required for a continuous wavetrain. Further study of human sensitivity to repetitive impulsive sounds may also be useful for minimizing the audibility of heavy lift rotorcraft blade passage harmonics.

6.2.6 Vestibular and visual effects

Vestibular effects include balance, nausea, giddiness, and other manifestations of a disturbance to the inner ear. Such effects are sometimes associated with nystagmus (the rapid involuntary oscillation of the eyeballs), and may reflect inconsistencies between information provided by the visual and vestibular system. Linkages between nystagmus and exposure to infrasound have been reported only under highly artificial conditions (out-of-phase diotic exposure at very low frequencies), and have been questioned by some researchers.

6.2.7 Respiratory, cardiovascular and other physiological effects

Elevated respiratory rate, choking, hypopharyngeal discomfort, and subcostal pressure have been reported at extremely high (~150 dB) infrasonic levels in acute exposure conditions in highly artificial laboratory settings. Pulse rate elevation and cutaneous flushing effects have likewise been observed in only small numbers of volunteers intentionally exposed to very high sound levels.

Reports of anxiety, balance/body sway, complaints, coughing, disorientation, drowsiness, euphoria, fatigue/tiredness, headache, inability to concentrate, irritability, malaise, nausea, pain on swallowing, restlessness, salivation, tenseness, testicular aching, vasoconstriction, vasodilation, and vertigo are likewise of little relevance for present purposes. The extreme levels necessary to produce such symptoms may be encountered during rocket launches and under conditions of military exigency, but are unrelated to routine civil transportation settings. Broner (2007) notes that such physiological effects "are unlikely to be of any practical importance except under extreme occupational exposure."

6.2.8 Speech interference/modulation

At very high infrasonic levels, chest wall vibrations and pulsating airflow in the vocal tract may distort speech, conceivably to the extent of reducing speech intelligibility. (Johnson (1971) even suggests that levels of about 166 dB at 1 Hz might be useful for artificial ventilation of the lungs.) According to Yeowart and Connor (1974), speech intelligibility may start to deteriorate in the presence of infrasonic levels as low as 115 dB. If such distortion becomes severe enough to impair air-ground and intra-cockpit voice communication, it could compromise flight safety.

6.2.9 Sleep disturbance

Reports of sleep disturbance in community settings are not uncommon among self-identified sufferers from low-frequency noise exposure. The phenomenon has not been rigorously investigated under controlled conditions, and has only marginal relevance for onboard tiltrotor exposure. Linkages between single event noise exposure and sleep disturbance are so tenuous (Michaud *et al.*, 2007) that documentation of potential sleep disturbance due to infrasound from tiltrotor operations is highly implausible.

6.2.10 Task interference

The reviews of Harris (1973) and Harris and Johnson (1978) of the effects of low-frequency, broadband, and infrasonic noise on cognitive and task performance strongly suggest that reports of adverse effects of infrasound on task performance are exaggerated. Except at sound pressure levels orders of magnitude greater than those likely to be encountered in a civil transport aircraft, noise-related deficits in task performance were found to be minor. The tasks most sensitive to interference from noise (hand tool dexterity and standing balance) are of little relevance to

potential tiltrotor passengers. For crewmembers, motivation generally suffices to overcome minor noise-related performance deficits.

6.2.11 Structural damage

Siskind and his collaborators (1976; 1980a and 1980b, 1989) report that residents express concerns with apparent structural damage risks from ground vibrations and airblast levels at levels as low as 120 dB at infrasonic frequencies. Objectively, such airblast levels are 60 – 70 dB lower than those that could in fact damage conventional residential structures in good repair, but community reaction may depend more on appearances and beliefs than on poorly-understood findings of engineering studies.

6.2.12 Combined effects of infrasound and vibration

Studies of the combined annoyance of low-frequency noise and concurrent sensible vibration have been most intensively studied in the context of disturbance caused by rail traffic. It is generally believed that the annoyance of combined low-frequency noise and structureborne vibration exceeds that of low-frequency noise alone. Öhrström and Skånberg (1996), for example, conclude that annoyance is greater in homes near rail lines in which substantial vibration occurs, particularly at low levels of noise. A laboratory study by Howarth and Griffin (1990) reached similar conclusions.

In another laboratory study of the annoyance of combined low-frequency noise and vibration, Paulsen and Kastka (1995) demonstrated that vibration influences the evaluation of annoyance due to noise alone. However, their results suggest a lesser degree of effect than that estimated by Howarth and Griffin (1990). A later study by Howarth and Griffin (1991) developed a method for predicting total annoyance produced by combined noise and vibration. Howarth and Griffin developed an annoyance index value, ψ, that is a function of both vibration and sound exposure levels, as show in Equation 8, below.

$$\psi = 22.7 + 243\,\phi_v^{1.18} + 0.265\,\phi_s^{0.036}$$

Equation 8

where φ_v is the vibration dose value and φ_s is the sound exposure level (where $\log_{10} \varphi_s = L_{AE}$).

The annoyance index is a relative one and has no absolute meaning outside the context of the paired comparison, magnitude estimation experimental paradigm. The following excerpt from the instructions to test subjects illustrates this point:

> *The first stimulus you will receive will be the reference stimulus and will be assigned the value of 100. The reference stimulus will be repeated before every four test stimuli. After each test stimulus please assign a number to indicate the annoyance that the combination of noise and vibration would cause if they were to occur together in your own sitting room.*
>
> *Try to make the ratio between the number you assign correspond to the ratio between the annoyance caused by the reference and the test stimuli. For example, if you consider that a test stimulus is twice as annoying as the reference stimulus, you should assign it the value of 200. Alternatively, if you consider it to be only half as annoying as the reference stimulus you should assign it the value of 50.*

Thus, Equation 8 is limited to indicating a growth of annoyance relationship with the noise and vibration variables, but does not attempt to relate this annoyance to that found in social survey based investigations.

6.3 Reviews of field studies

Several recent studies of community reaction to low-frequency aircraft noise have been concerned less with the annoyance of aircraft noise *per se*, than with the annoyance of secondary emissions (rattle) induced in residences by aircraft ground operations.

6.3.1 Fidell, Silvati, Pearsons, Lind, and Howe (1999)

Fidell *et al*. (1999) completed interviews with 644 residents of a runway sideline neighborhood adjacent to a pair of busy runways at Los Angeles International Airport. The questionnaire focused on the annoyance of rattling sounds produced by aircraft thrust reverser and departure noise. Figure 69 shows the locations of survey respondents who described themselves as highly ("very" or "extremely") annoyed by such rattling sounds. Although the homes of many respondents who were highly annoyed by rattle are within about half a mile of the runways, others live at yet greater distances.

The contours shown in Figure 69 are isopleths of a suggested single-event, low-frequency aircraft noise metric known as "Low-frequency Sound Level", or LFSL. The measure extends over the six one-third octave bands centered at 25-80 Hz, which encompasses the frequency region in which high bypass ratio jet engines for large transport aircraft generate most of their low-frequency noise. The lower bound of the LFSL metric is an octave or two higher than the expected fundamental rotor passage frequency for large civil rotorcraft, but includes the region of the first few harmonics.

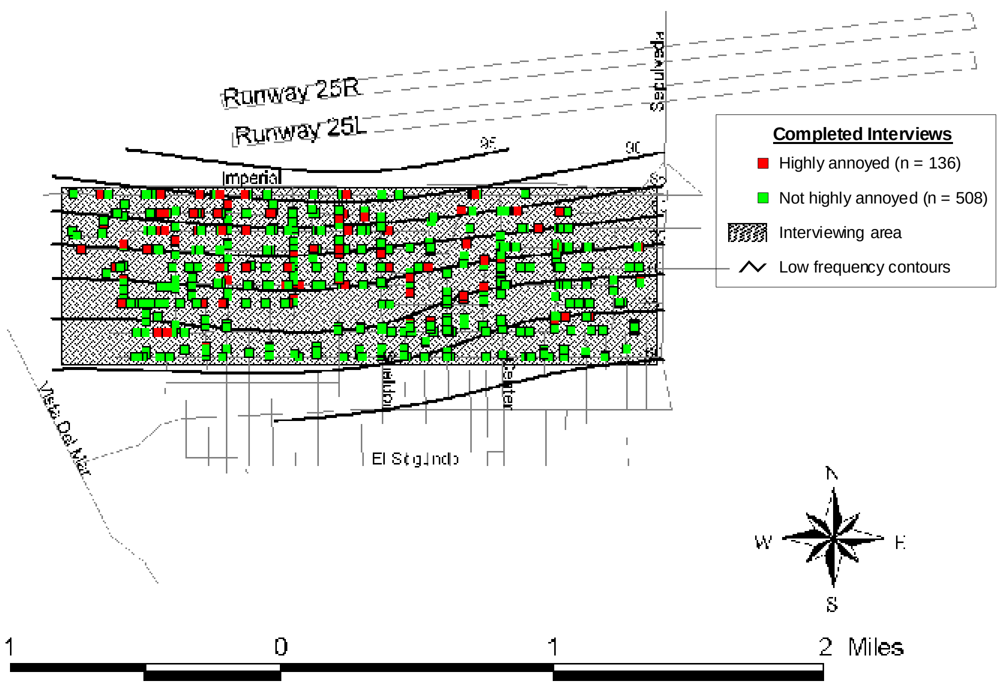

Figure 69: Low-frequency noise contours (reproduced from Fidell *et al*., 1999).

6.3.2 Fidell, Pearsons, Silvati, and Sneddon (2002)

Fidell *et al*. (2002) conducted a near-replication of the LAX study described above at Minneapolis-St. Paul International Airport (MSP). Interviews were completed with 495 residents whose homes were located within about half a mile of runway sidelines. The findings of the MSP study were similar to those reported earlier with respect to the types of objects cited as sources of rattle in homes, frequencies of notice of rattle, and the prevalence of annoyance due to aircraft noise-induced rattle. Figure 70 is a dosage-effect relationship between low-frequency sound levels and the prevalence of high annoyance with low-frequency aircraft noise-induced rattle in homes near runway sidelines at both LAX and MSP.

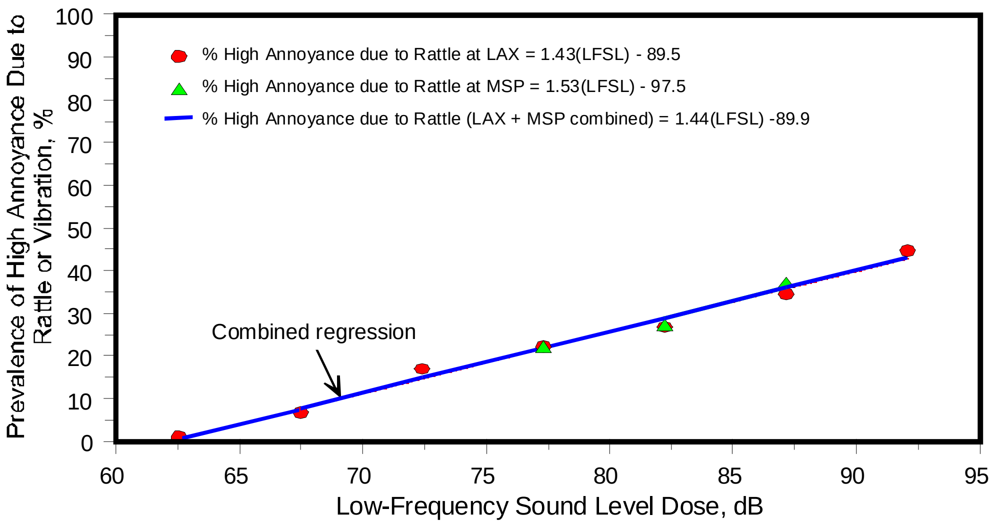

Figure 70: Observed prevalence of annoyance due to rattle and vibration (from Fidell *et al*., 2002)

The DNL value at which FICON considers A-weighted aircraft noise creates a significant noise impact is 65 dB. At this level, FICON's dosage-effect relationship predicts that 12.3% of the population is highly annoyed by aircraft noise exposure. The LFSL value at which 12.3 % of the population is highly annoyed is by aircraft noise-induced rattle is 71 dB. Figure 71 shows that such noise levels occur at ranges on the order of 4,000 feet from runway sidelines.[20] Thus, if infrasound at fundamental frequencies and harmonics of tiltrotor blade passage rates create are no more effective than thrust reversers at creating rattling sounds inside residences, their operations may create appreciable annoyance at ranges in excess of half a mile from their operating sites.

[20] Note that both Figure 70 and Figure 71 are source-specific; *i.e.*, derived from and most appropriate for predicting community response to intermittent, broadband, low-frequency noise, such as that produced by large jet engines which power transport aircraft. Main rotor and first harmonic tonals from tiltrotors at frequencies closer to the resonances of wood frame residences could induce yet more rattling and annoyance than such engines.

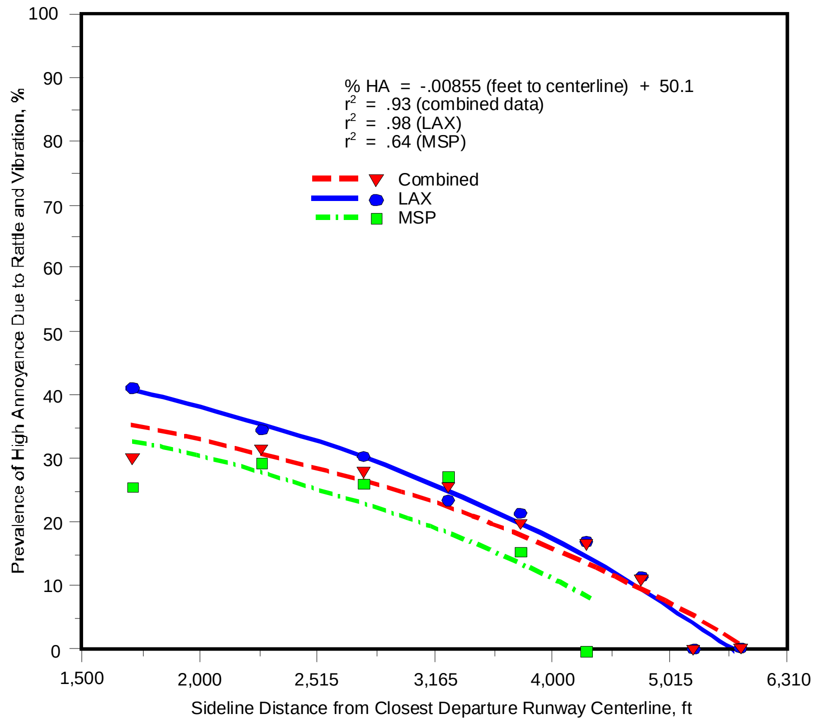

Figure 71: Geographic association between proximity to runway sidelines and the prevalence of annoyance due to rattle caused by low-frequency aircraft noise (from Fidell *et al*., 2002).

6.3.3 Hogdon et al. (2007)

Hogdon *et al*. measured low-frequency noise created by aircraft ground operations (start-of-takeoff-roll, sideline acceleration, and thrust reverser applications) at Dulles International Airport at runway sidelines, and in a brick and a stone house about half a mile from the runways. Their measurements confirmed prior observations that takeoffs and landings create substantial airborne low-frequency noise and structureborne vibration at ranges of at least 3,000 feet from airport runways, and that A-weighted measurements do not usefully characterize the low-frequency content of near-ground aircraft noise.

Both the low-frequency noise itself, and the rattle that it can induce in light architectural elements such as windows, doors, and household paraphernalia, can create residential annoyance. Hogdon *et al.* also conclude that aircraft noise at frequencies below 50 Hz is instrumental in causing rattle in structures.

Measured levels of structural vibration associated with rattle were imperceptible by human observers. In paired comparison subjective judgment tests, multiple measures of low-frequency noise levels correlated well with annoyance judgments. None of the physical or subjective measurements made by Hogdon *et al.* were directly relevant to the infrasonic rotor noise that a large civil tiltrotor will create.

6.3.4 Jensen, Lund and Lücke (2008)

Jensen *et al.* examined health records of 42 Danish Air Force flight line maintenance workers routinely exposed to high levels of low-frequency noise. During launches of F-16 fighter aircraft, these workers accumulate annual exposures on the order of 25 hours to low-frequency noise at peak levels as great as 144 dB and equivalent levels of 124 dB. The mean duration of employment of the flight line workers was nearly 20 years.

No meaningful differences in diseases or reported symptoms were found in comparisons of the extra-auditory health of flight line workers with those of matched aircraft mechanics unexposed to flight line noise. Although hearing loss was higher among the flight line workers than among the mechanics, no differences were found in blood pressure, lung function, or in values of hemoglobin, cholesterol and liver enzymes, and nausea and headache were less common among the flight line workers than among the mechanics. Jensen *et al.* conclude that their findings do not support the hypothesis that exposure to high noise levels (including high levels of low-frequency noise) induces disease in organs other than the ear.

6.3.5 Manley, Styles, and Scott (2002)

This is another report of small-scale case study investigations of residential complaints about low-frequency noise. Much of the article concerns pragmatic concerns with instrumentation required for measuring low-frequency noise. No substantive conclusions are reached about public perceptions of low-frequency noise (the ostensible focus of the study), but the authors do offer the conjecture that "some apparently paranormal sightings are in fact caused by infrasound."

6.3.6 Møller and Lydolf (2008)

The findings of Møller and Lydolf are similar to those of a number of other speculative and inconclusive northern European and Japanese investigations (e.g., Manley *et al.*, 2008; Qistdorff and Poulsen, 2008; Kitamura *et al*., 2008) of complaints attributed to low-frequency or infrasonic noise disturbance. Møller and Lydolf mailed an unverifiable number of copies of a loosely-structured written questionnaire with open-ended responses to a non-representative sample of known complainants. A total of 198 returned questionnaires were reviewed by the authors, who were unable to draw any definitive conclusions about potential external sources, levels or other characteristics of the offending low-frequency sounds.

Peer-reviewed or not, studies in which non-specific low-frequency noise complaints are investigated are unlikely to offer much guidance useful for current purposes, since the sources of infrasound and low-frequency noise associated with tiltrotor operations are likely to be very evident to heliport neighbors.

6.3.7 Persson Waye and Rylander (2001)

The authors compare and extensively discuss written answers provided by 108 respondents living in homes with low-frequency energy (supposedly from heat pumps and HVAC systems, at levels of about 60 dB at frequencies around 50 Hz) with those of 171 respondents in homes with somewhat lower low- and mid-frequency sound levels. Methodological details of questionnaire administration and noise measurements are sketchy but plausible, whereas actual exposures of residents to specific levels of low-frequency noise are difficult to estimate.

Sound pressure levels at frequencies below about 40 Hz in the homes of respondents with supposedly prominent low-frequency energy appear to have been largely inaudible (no greater than about 45 dB). Comparable levels in the homes of control respondents may have been about 10 dB lower in the same frequency range, but also 5 to 10 dB lower at higher frequencies as well. Noise levels inside dwellings do not appear to have been generated by outdoor sources.

Persson Waye and Rylander found no evidence of any greater incidence of self-reported medical symptoms among respondents living in homes with the higher levels of noise in the 50 Hz region. They also speculated that modestly elevated levels of annoyance among respondents from homes with low-frequency HVAC noise may have been due to sleep disturbance. Since the homes of respondents lacking 50 Hz noise from HVAC systems also appear to have been about 5 dB quieter at higher frequencies than the homes with such noise, the speculation is not entirely compelling.

6.3.8 Rushforth, Moorhouse, and Styles (2003)

Rushforth *et al*. report a case study which they interpret as supporting the utility of a particular set of one-third octave band limits (German Standard DIN 45680, 1997) as useful guidance for diagnosing low-frequency noise problems. After introductory text alluding to an alarming list of supposed health hazards and "psychosocial and mental health effects" of exposure to low-frequency noise, and invoking individual differences in sensitivity to low-frequency noise as explanations for the "unbearable" nature to some of low-frequency noise that others find unexceptional, the authors recommend the one-third octave band levels shown in Table 9 (from DIN 45680) as useful for identifying low-frequency noise problems – particularly for tonal or amplitude modulated ("throbbing") low-frequency sounds. Shown in Figure 72, the curve connecting the DIN 45680 data points lies slightly below both the ISO 389-7:1996 free-field pure tone threshold of hearing and the threshold synthesis work of Møller and Pedersen (2004) in the infrasonic frequency region.

The authors' endorsement of the levels shown in Table 9 is based on identification of tonal energy at 12.5 and 38 Hz in field measurements made in three homes.[21] Apart from some acoustic measurements, the case study offers no quantitative support for the authors' beliefs about the adequacy of the levels identified in DIN 45860. For example, the authors simply observe that after some noise control efforts in a factory near complainants' homes, "the level of complaints received by the local council dropped considerably."

[21] The authors also observed considerable broadband energy in the 50 and 63 Hz bands that exceeded the DIN 45680 levels, but considered it unlikely to be the basis of the noise complaints because it was non-tonal, and hence not "unusual" within the meaning of the standard.

Table 9: Nighttime low-frequency one-third octave band levels identified as limits of acceptable single-event noise levels in DIN 45680[22]

1/3-Octave Band Center Frequency (Hz)	10	12.5	16	20	25	31.5	40	50	63	80	100
1/3-Octave Band Sound Pressure Level (dB)	95.0	86.5	79.0	71.0	63.0	55.5	48.0	40.0	33.5	33.0	33.5

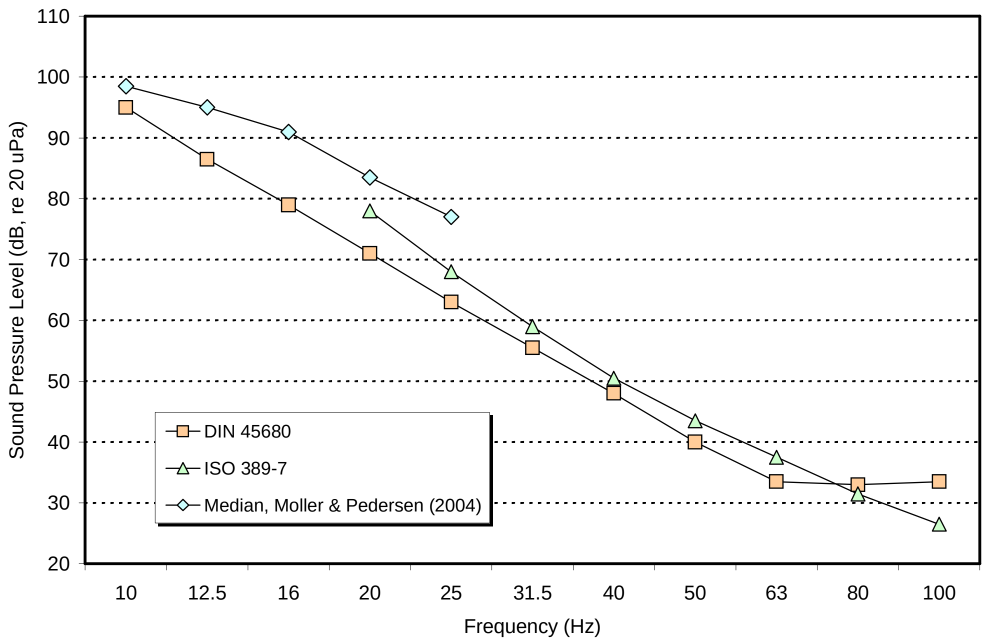

Figure 72: Comparison of DIN 45680 and ISO 389-7:1996 Hearing Threshold

6.4 Reviews of secondary sources

The secondary literature summarizing and interpreting infrasonic effects may well exceed the quantity of original empirical studies applicable to tiltrotor interests. Entire journals are devoted to low-frequency noise; handbooks and reference works, such as Crocker (2007), Harris (1991), Kryter (1984) and May (1978) summarize and discuss findings of infrasound studies; well-known, book-length compendia of chapters on specialized aspects of infrasound have been published (notably Tempest, 1976, and Hansen, 2007); and a fair number of review articles and reports are readily available (*e.g.*, Westin, 1975; Broner, 1978; Backteman, Köhler, and Sjöberg,

[22] Stated scope: "These guidelines should provide some criteria for the assessment of low-frequency noise immissions in the neighbourhood according to DIN45680. It are intended for the application to noise immissions caused by industrial plants and should complete the existing methods for the assessment of these immissions."

1983; Leventhall, 2003/2004; Schust, 2004). Some of these reports and reviews are thorough and extensive, while others are perfunctory and lacking in methodological detail.

6.4.1 Berglund, Hassmén, and Job, (1996)

This review article paraphrases and interprets previously published primary information about infrasonic effects, as well as findings of studies of exposure to sound in frequency ranges higher than the rotor passage rates of present interest. Berglund *et al.* broadly consider acoustic energy at frequencies below 250 Hz as "low-frequency" noise.[23] Within this range, they further identify the spectral range below 10 Hz as "infrasound (with body resonances)"; the octave from 10 to 20 Hz as "infrasound"; and the next higher 3+ octaves as "noise".

Although Berglund *et al.* acknowledge (via citation of von Gierke and Nixon's chapter in Tempest's 1976 book) that mechanisms of "hearing" at infrasonic frequencies differ from those at higher frequencies, they nonetheless plot eight sets of estimates of "hearing" thresholds at frequencies from 1 Hz through 100 Hz.[24] . Figure 73 shows their estimates. Further discussion of low-frequency threshold estimates may be found in section 6.4.10 (Møller and Pedersen, 2004).

Berglund *et al*. next remark that transportation machinery exposes much of the population to low-frequency noise, as shown in their Figure 3 (reproduced here as Figure 74). The authors fail to note that community exposure to infrasound produced by most transportation noise sources is experienced at levels below 100 dB, and thus fails by 20 dB or more to reach the threshold of hearing estimates shown in both Figure 73 and Figure 77, even ignoring the influences of masking noise of other origin on audibility of infrasound.

The same issues of (in)audibility hold for infrasound in communities produced by impulsive sources (jack hammering, pile driving, blasting, artillery, and the like); for the audibility of infrasound produced by wind turbines; for the audibility of ambient infrasound in urban areas; for infrasound produced by commercial transport aircraft; and even for the infrasonic occupational exposure that Berglund *et al.* plot in their Figures 4 through 8.

Section IV of Berglund *et al.* notes in passing that low-frequency noise can induce both structure-borne vibration and vibration in people's bodies, and that low-frequency vibration that is correlated with airborne infrasound can contribute to the noticeability of infrasound. They also attribute doubts about the adequacy of older measurements of low-frequency noise to limitations of pre-digital instrumentation, and to loose tolerances in filter network specifications. Berglund *et al*. then comment on the paucity of direct empirical data on which to base equal loudness and equal noisiness contours, and on unresolved conflicts in interpretations of the findings of field studies of low-frequency noise effects.

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[23] "In the present review noise below 250 Hz is considered to constitute low-frequency noise." (p. 2986)

[24] Berglund *et al*. do not normalize or otherwise adjust any of the estimates to comparable bandwidths or other measurement conditions. Matsumoto *et al.* (2008) have shown that bandwidths of low-frequency sounds (*e.g.*, pure tones *vs*. narrow bands of noise) can substantially affect hearing thresholds, and that higher frequency artifacts accompanying low-frequency signal presentations can affect apparent low-frequency hearing thresholds as well.

Section V of Berglund *et al.* begins with an assertion that 1) the relative acoustic transparency of structures at low frequencies and 2) the pervasiveness of low-frequency acoustic energy “make noise a factor of critical importance to health”. The persuasiveness of this reasoning plainly depends on one’s definition of “health”, and the frequency region of concern.

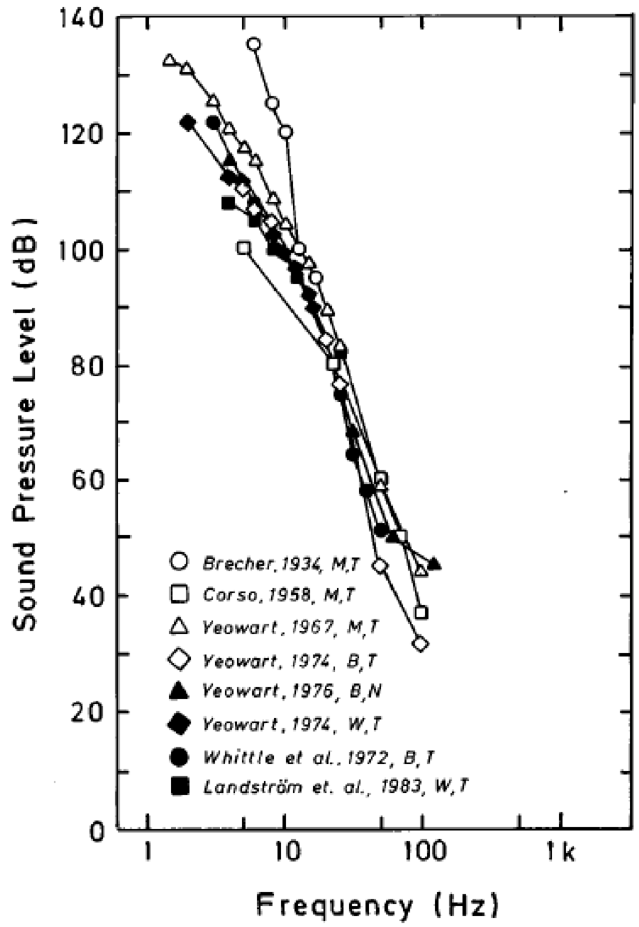

Figure 73: Comparison of low-frequency and infrasonic absolute threshold estimates (reproduced from Berglund *et al.*, 1996).

A table (adapted from von Gierke and Nixon, 1976) then summarizes findings of half a dozen reports of temporary threshold shift (TTS) at infrasonic frequencies induced by exposures of seconds to hours, at sound pressure levels as great as 171 dB. In this sparse set of studies, roughly half (or fewer) of the small numbers of test participants exhibited TTS, generally of less than 20 dB. Recovery from TTS typically occurred within 30 minutes of the cessation of exposure. Relative to TTS induced by comparable levels and durations of noise exposure at higher frequencies, TTS attributable to exposure to infrasound is hardly alarming.

Berglund *et al.* report no evidence of permanent threshold shifts due to exposure to infrasound. They cite only two estimates of thresholds of aural pain: 155 dB at 5 Hz, and 135

dB at about 50 Hz.[25] These estimates were based on the findings of von Gierke *et al*. (1953) and of Bekesy (1960) which are summarized by von Gierke (1974, Figure 10) with claims that results are "highly consistent." These findings suggest that "audible" rotor fundamental tones are less likely than harmonics to be considered painfully loud by tiltrotor crew and passengers.

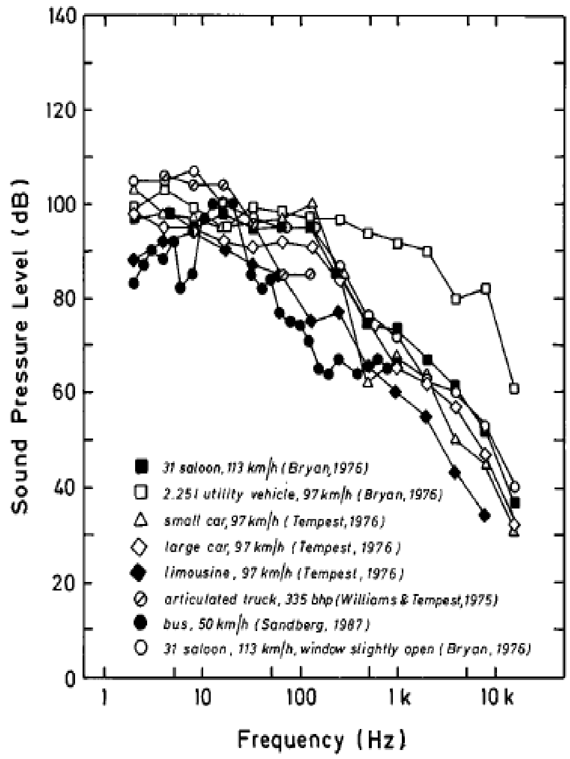

Figure 74: Noise spectra associated with road traffic sources (reproduced from Figure 3 of Berglund *et al*., 1996).

The remainder of Section V of this review paper catalogs a miscellany of accounts of effects attributed to infrasound in the vestibular, respiratory, cardiovascular, and endocrine systems, along with reports of annoyance, interference with performance, cognition, sleep, mental health, communication, and "psychosocial" interactions. As Berglund *et al.* note concerning the cardiovascular effects in particular, many of these effects "are not uniformly observed" and "are of unclear clinical significance."

Some of the putative effects discussed are not clearly attributable to infrasound (or even to low-frequency sound), including claims of elevated blood pressure in school children exposed to aircraft noise. Berglund *et al.* explicitly concede the point with respect to supposed mental health effects: "Examination of mental health effects of pure low-frequency noise is not feasible since pure sources occur rarely in the real world."

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[25] Broner attributes to Nixon and Johnson (1973) further estimates of the threshold of pain at 2 Hz and 20 Hz as 162 and 140 dB, respectively.

Section VI of Berglund *et al.* describes some of the many methodological difficulties in drawing valid inferences from laboratory and field studies. For laboratory studies, these difficulties include a variety of statistical and control issues, as well as difficulties in generating and measuring infrasonic energy, generalizing from acute to chronic exposure conditions, ethical concerns (with risks of physiological harm and inadequate informed consent), and the like. For field studies, the difficulties include the well-known weaknesses of correlational study designs, and even greater confounding in naturalistic settings (than in the laboratory) of infrasonic and other sounds.

Although Berglund *et al*. are well aware of the methodological weaknesses of the research literature, and draw no specific, substantive conclusions from it, they nonetheless assert that "The balance of probability would appear to favour (*sic*) the conclusion that noise has a variety of adverse effects on humans, both physiological and psychological." Without qualifying this apparent conclusion with reference to specific durations, frequency ranges, or exposure levels, the authors also counsel similarly non-specific "concerned action" without "waiting for definitive proof that may never arise."

Berglund *et al*. also express the view that infrasound can "have an effect even without conscious (auditory) detection"; in other words, that inaudible infrasound may be harmful in some way.

6.4.2 Broner (1978, 2007)

Broner's 1978 review of then-recent studies of the effects of infrasound and low-frequency noise on people reaches distinctly different conclusions from those of Berglund *et al*. Broner views the effects of low-frequency noise as "similar to those of higher frequency noise"; considers that "noise in the 20 – 100 Hz range is much more significant than infrasound at similar sound pressure levels"; and that "the possible danger due to infrasound has been much over-rated."

It follows from Broner's views that annoyance is the principal consequence of low-frequency and infrasonic exposure at continuous sound pressure levels less intense than those of rocket launches, and at impulsive levels lower than those of airbags and artillery fire. He speculates about large individual differences in hearing thresholds at low frequencies, and about the role of spectral "balance" (the relative energy content at very low and somewhat higher frequency regions, or what architectural acousticians call "rumble") in determining the annoyance of sounds with large amounts of low-frequency and infrasonic energy.

The remainder of Broner's 1978 review addresses noise effects such as hearing thresholds, temporary threshold shifts, aural pain, fullness in the ears, equilibrium, dubious claims in the popular press of dire consequences of low-frequency noise exposure, as well as better documented studies of physiological and performance effects.

Broner's discussion of performance decrements associated with very low-frequency exposures is comprehensive for its day. After identifying nine studies reporting some form of performance decrement, he identifies another dozen with ambiguous, insignificant, or even contrary findings, including some suggesting the possibility of a performance-sustaining arousal effect of infrasonic exposure.

Broner eventually concludes with cautions about over-interpreting the findings of methodologically weak studies of infrasound and low-frequency noise effects. He also restates his belief that the consequences of exposure to higher frequency sounds of comparable levels are more notable than those of exposure to infrasound, and that the effects of exposure to sounds in the range of 20 – 100 Hz are of greater concern than exposure to sounds of comparable level at yet lower frequencies. Although Broner's views seem apt in many commonly-encountered settings, they do not necessarily apply specifically to the cockpit and cabin of a heavy lift civil tiltrotor.

Broner's 2007 review makes few additional points, but provides some additional rules of thumb. He indicates, for example, that differences of 15 - 25 dB between A-weighted and linear sound pressure levels suggests the presence of low-frequency noise that can be very annoying despite relatively low A-weighted levels. Broner's later review also draws further attention to fluctuations in infrasonic levels, such as periodic throbbing, as an important source of annoyance.

6.4.3 Evans (1976)

Evans' review focuses on laboratory studies of effects of moderate-level infrasonic exposure, including involuntary effects (such as her own studies of nystagmus in seated test subjects) and performance effects (such as balance, manual dexterity, pointer following, reaction time, and number recognition, among others).[26]

Evans and her co-workers (Evans, Bryan and Tempest, 1972; Evans and Tempest, 1972) were able to reliably induce vertical nystagmic movements via out-of-phase headphone presentation of unspecified (but presumably tonal) signals at seven frequencies between 2 Hz and 20 Hz. The onset and duration of nystagmus were both level- and duration-dependent. Although nystagmus was clearly driven by the acoustic signals, the eye movements were not synchronized with the infrasonic signals in the headphones. Self-reports of test participants described the sensations as mildly unpleasant, and of drowsiness.

Evans interprets the vertical nystagmic movements as ocular compensation for the sensation of apparent motion due to stimulation of the anterior vertical semi-circular canal, and perhaps of the otoliths. Given the highly artificial nature of diotic antiphase presentation of acoustic stimulation, it is doubtful that in-cabin or in-cockpit exposures to in-phase tiltrotor blade passage frequencies would create such strong nystagmic responses.

Evans and Tempest (1972) also exposed the same test participants to whole-body infrasound at levels as high as 137 dB. Their subjective impressions are summarized in Figure 75.[27] Evans also summarizes a number of balance and human performance measurements made by Hood and Leventhall (1971) and by Hood, Leventhall, and Kyriakides, 1972), most of which yielded only minor or inconclusive findings. The main response of test subjects to infrasound at levels above 120 dB was characterized as "arousal".

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[26] Much of this work has been criticized by Harris *et al.* (1976), who questioned the logic, methods, and findings of the work reviewed, and failed to replicate some of the findings (albeit in somewhat different experimental conditions.)

[27] Note, however, that other researchers (*e.g.*, Harris) have challenged some of these interpretations, and that few of the summarized findings have been extensively replicated.

(1) *Frequency range 2-5 Hz: SPL range 100-125 dB*

(a) Movement of the eardrum in response to the pressure changes.
(b) Pressure build-up in the middle ear.
(c) Difficulty in swallowing, all subjects were persistently trying to swallow as a mechanism for pressure release.
(d) Slight post-exposure headaches which were not persistent.

(2) *Frequency range* 2-5 *Hz: SPL range* 125-137.5 *dB*

(a) Movement of the eardrum.
(b) Difficulty in speaking and voice modulation.
(c) Chest wall vibration.
(d) Swaying sensations as if falling.
(e) Lethargy and drowsiness.
(f) Slight tinnitus at frequencies above 10 Hz.
(g) Post-exposure headaches and fatigue.

(3) *Frequency range 5-15 Hz: SPL range 125-137.5 dB*

(a) Movement of the eardrum.
(b) Middle-ear pain.
(c) Difficulty in speaking and voice modulation.
(d) Severe chest wall vibration.
(e) Severe abdomen vibration and associated feelings of nausea.
(f) Falling sensations.
(g) Lack of concentration and drowsiness.
(h) Tinnitus.
(i) Severe post-exposure fatigue and headaches.

(4) *Frequency range 15-20 Hz: SPL range 125-137.5 dB*

(a) Severe middle-ear pain.
(b) Respiratory difficulties-gagging sensations. In one case spasms of uncontrollable' coughing developed.
(c) Nasal cavity vibration.
(d) Persistent eye watering.
(e) Tinnitus. .
(f) All subjects experienced sensations of fear including excessive perspiration and shivering, these symptoms decreased with successive exposures.
(g) Severe post-exposure fatigue and headaches.
(h) In two cases (both female) cutaneous flushing.

Figure 75: Subjective impressions of exposure (reproduced from Evans, 1976)

6.4.4Fidell, Harris and Sutherland (2000)

The report of the Richfield-MAC Low-Frequency Noise Expert Panel contains extensive analyses of the effects of low-frequency aircraft and other noise sources on structures and communities, including a 60-page review of 150-odd technical references. The report identifies levels of low-frequency sound in the frequency range of 25 – 80 Hz associated with a prevalence of annoyance due to aircraft noise-induced rattle comparable to those which FICON (1992) views as a threshold of concern for federal participation in noise mitigation projects.[28]

The report also contains an extensive literature review, syntheses of the vibration-induced structural rattle literature, results of both laboratory and field low-frequency measurements of full-scale structural noise reduction, field measurements and analyses of thrust reverser noise, a social survey of reactions to low-frequency aircraft noise, and analyses of these and other findings.

6.4.5 von Gierke (1973)

von Gierke's presentation at this Colloquium is a narrative-style summary of the findings of two decades of laboratory studies of studies of physiological and behavioral effects of acute (one-time, short-duration, high-level) exposures to infrasound. Much of this work was intended to identify maximum tolerable exposure limits, initially estimated as 140 dB for aircrew and 120 dB for nearby communities and ground crew. Limits of voluntary exposure to infrasound were encountered at about 150 dB, due to discomfort with pressure buildup in the middle ear, and tickling and choking sensations in the throat. (The latter were attributed to drying effects on sensitive membranes of infrasonic pumping of air through the trachea.) von Gierke and his co-workers also concluded that the greater problem with high-level low-frequency noise exposures is in the range above 30 Hz, where visual acuity was more greatly affected than at infrasonic frequencies.

Effects of infrasound on the vestibular system were also investigated, in part in animal preparations. It was concluded that effects on balance were negative or *de minimis* in humans at levels below 150 dB. von Gierke next addresses frequency differences in body resonances for vibration and infrasound, noting that the former are about a decade lower (in the 4 to 8 Hz octave) than the latter (in the 40 to 60 Hz range).

The final conclusion from the early studies conducted at the Aerospace Medical Research Laboratory discussed in the presentation is that "sound effects are smaller for the same pressure level in the infrasound range than they are in the audio frequency range."

6.4.6 Hansen (2008)

Hansen's book is a compendium of articles published between 2000 and 2005 by the Journal of Low-frequency Noise, Vibration, and Active Control. The findings of individual studies collected by Hansen are reviewed elsewhere throughout this report.

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[28] Although the frequency range of concern in the Expert Panel report is more than two octaves higher than the expected fundamental frequency of tiltrotor blade passage rates, it encompasses the frequency range of several tiltrotor harmonics.

6.4.7 Harris (1973)

Harris's presentation at the 1973 "Noise as a Public Health Hazard" conference reviews much of the work on high intensity noise exposure effects conducted at Wright-Patterson Air Force Base from 1965 through 1973. Only a relatively small portion of this work involved low-frequency or infrasonic noise exposure, and the work cited involved people with hearing protection in place.

6.4.8 Harris, Sommer, and Johnson (1976)

Harris *et al.* (1976) note the absence of clear empirical demonstrations of adverse effects of infrasound on task performance, and in particular, of any direct link to nystagmus. They characterize reports of such effects at levels of infrasound less than 120 dB as exaggerated, and note that adverse effects are poorly documented even at higher levels. They concede, however, that hazardous levels remain unknown.

6.4.9 Johnson (1973)

Most of this review of whole-body human and animal infrasonic exposure studies focuses on the absence of non-auditory effects of intense infrasound on infra-human primates and dogs, and on chinchilla hearing. Some anecdotal information is presented about voice modulation at infrasonic levels in the 120 – 145 dB range, from which Johnson concludes "Speech intelligibility under critical conditions under high task loading and other environmental stressors must be further studied." Figure 76 summarizes Johnson's view that infrasonic exposures at levels below about 130 dB (at 1 Hz) to 120 dB (at 20 Hz) have no adverse physiological consequences for humans.

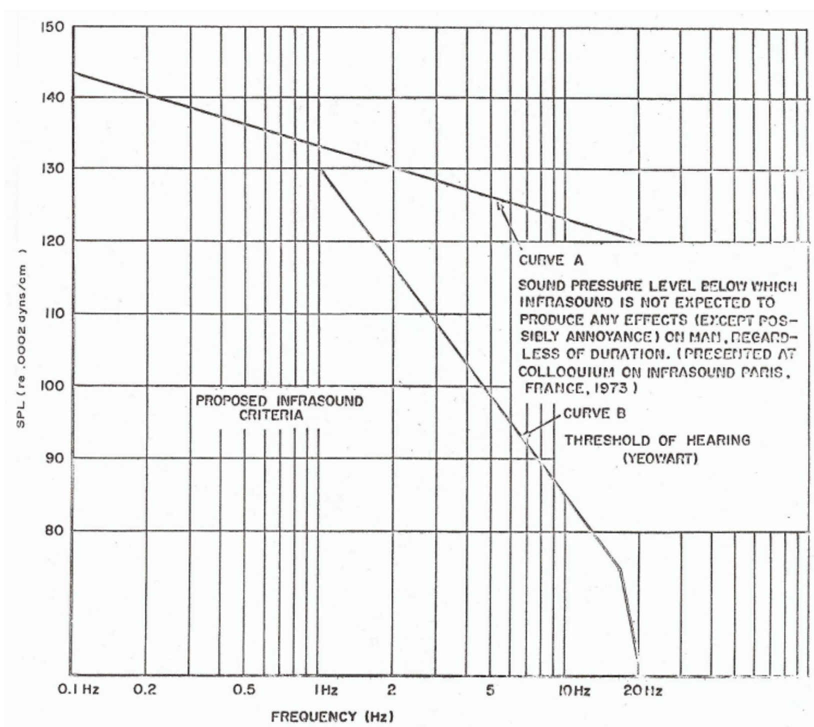

Figure 76: Johnson's (1973) summary of levels of infrasound that have no adverse physiological consequences.

6.4.10 Møller and Pedersen (2004)

Møller and Pedersen (2004) review more than fifty publications on hearing sensitivity at frequencies below 200 Hz, from Sivian and White's 1933 early review article, to recent European and Japanese experimental studies of low-frequency hearing thresholds and loudness contours. They note that even though hearing thresholds are not standardized at frequencies lower than 20 Hz, reasonable agreement prevails among published reports of sensitivity at lower frequencies.

Figure 77 presents a compendium of the more recent threshold information, reproduced from Møller and Pedersen (2004). Estimates of audible infrasonic sound pressure levels vary over a range of about 45 dB - from about 130 dB to about 85 dB - in the region from 1 to 20 Hz, and over another 55 dB range - from about 85 dB to 30 dB - in the region from 20 to 100 Hz. The figure compares the data with the threshold defined in the ISO 226 (2003) loudness level standard (whose threshold data has been superceded by the free-field curve shown in ISO 389-7 (1996).

In this figure, the monaural findings of Yeowart (1967) have been reduced by 3 dB to account for the expected improvement in threshold performance attributable to binaural over monaural listening, called the "binaural advantage." Møller and Pedersen justified this expectation at low frequencies by citing three studies in which monaural and binaural listening were performed by the same test subjects. The results are reproduced here as Figure 78. In the figure it may be seen that this difference is not just a mid-range and high-frequency phenomenon. In fact, the data show the effect persists down to a frequency of 3 Hz. The effect is tantamount to assuming that threshold is an internal masking noise phenomenon, whereby the summation process across the two ears is one in which the signal (a sinusoid) adds coherently, and the uncorrelated internal masking noise in each ear adds incoherently, resulting in an improved signal-to-noise ratio of 3 dB. (Note that the data by Yeowart and Evans, 1974 marked "equalized" refer to the condition, where signals have been adjusted to obtain equal sensation at the two ears during the binaural exposure.)

Møller and Pedersen attribute the revisions made in 2003 to ISO's 1987 equal loudness contours at very low frequencies to bias in the data collected by Robinson and Dadson (1956). According to Møller and Pedersen, the adaptive psychometric data collection methods employed in subsequent determinations of low-frequency equal loudness studies are more reliable than those of Robinson and Dadson.

Møller and Pedersen also note that the sensation of pitch ceases at about 20 Hz[29]; that the sensation of tonal signals at lower frequencies becomes discontinuous and discrete; and that individual cycles of periodic signals become noticeable at frequencies below about 10 Hz. They find little reason to suspect age and gender differences in infrasonic sensitivity.

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[29] Evans (1976) and Broner (1978) characterizes infrasonic tones as producing "chugging," "rough," "whooshing" or "popping" sounds. Johnson and von Gierke suggest that such sensations may be distortion products produced in the middle and inner ear, or higher harmonics of infrasound.

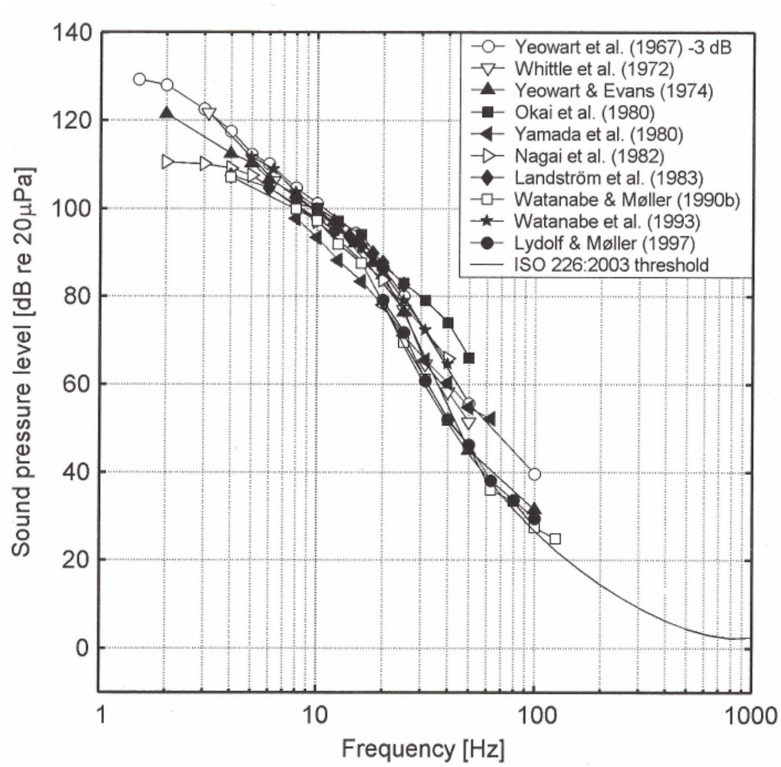

Figure 77: Comparison of low-frequency and infrasonic absolute threshold estimates (reproduced from Møller and Pederson, 2004).

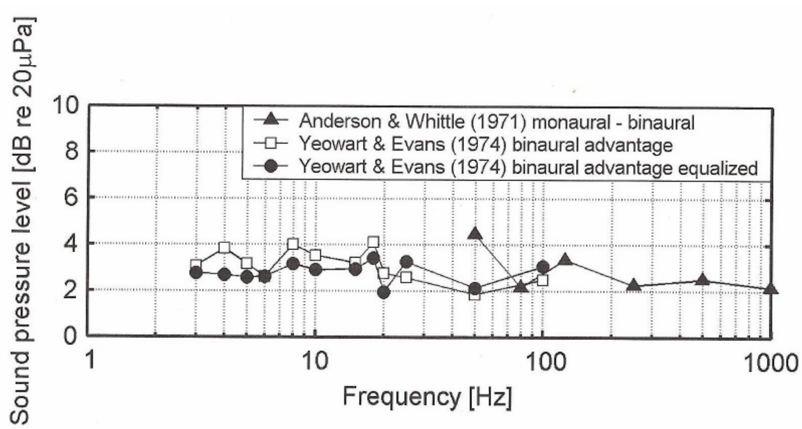

Figure 78: The difference in thresholds between monaural and binaural exposure (from Møller and Pedersen, 2004, Figure 6).

Møller and Pedersen further point out that the dynamic range of the auditory system decreases markedly with frequency, to the point that very little "headroom" remains between barely audible and very loud (if not painful) sounds at very low frequencies. They reiterate observations of "pressure at the eardrums" at infrasonic frequencies, described elsewhere as "fullness in the ears."

6.4.11 Nixon (1973)

Nixon's presentation at the 1973 Paris Colloquium focuses on hearing-related consequences of very high levels of exposure to infrasound. At infrasonic levels around 125 dB, subjects in studies conducted by Nixon reported that their tympanic membranes felt as though they were being massaged at the same rate as the exposure frequency. At levels a few decibels greater, pressure in the ears was commonly reported, and a slight reddening of the surface of the eardrum can be observed. At yet higher levels "aural discomfort" was reported, followed by aural pain at extreme levels of infrasound.

Although small (5 – 10 dB) temporary threshold shifts were observed in about a third of test subjects exposed to infrasound at levels of 135 dB, some of these may have been due to harmonic distortion products at higher frequencies.

The remainder of Nixon's discussion concerns impulsive noise sources and hearing protection issues that are of only slight relevance to tiltrotor cockpit and cabin exposure issues.

6.4.12 Persson Waye (2004)

The only original quantitative finding reported by Persson Waye (2004) is that approximately two-thirds of a self-selected group of 198 respondents to a written questionnaire experienced insomnia and concentration problems which the author speculates might have been associated with unknown exposure to low-frequency noise. Persson Waye made the questionnaire available for a period of 16 months to unknown numbers of potential respondents through local governments, interest groups, and on the Internet. Even though the report appears in a peer-reviewed journal, the author indicates that "no objective information [about noise exposure] was available for most of the cases". Likewise, no information is presented about the wording of the questionnaire, nor the representativeness of the sample.

The remainder of Persson Waye's article argues that "A limited number of epidemiological studies have been carried out which give some support to the findings" of the questionnaire study. These include small-scale case studies by Mirowska (1998), and other studies reported by the author and collaborators in conference proceedings. The author also notes, however, that Persson Waye and Rylander (2001) found no meaningful differences in self-reported sleep quality "among people exposed in their homes to flat frequency noise as compared to low-frequency noise from ventilation/heat pumps."

Persson Waye's summary of effects of low-frequency noise on sleep underscores the dearth of information about the topic useful for formulating criteria for tiltrotor design and operation.

6.4.13 Schomer (2004)

Schomer argues in this paper that the (level-specific) loudness level frequency weightings provide "much better correlation with subjective annoyance responses than does A-weighting", particularly for very low-frequency sounds. Schomer attributes the superiority of loudness level-weighted sound exposure levels (LLSEL) to A-weighted sound exposure levels (SEL) as predictors of annoyance both to the level dependence of the loudness contours, and to the convergence of contours at low frequencies, as shown in Figure 79.

For example, Schomer notes that a 10 dB change in sound pressure level in the frequency range from about 250 Hz to 2000 Hz is associated with a 10 dB change in loudness, whereas at

31 Hz, a 10 dB change in sound pressure level is associated with a 20 dB change in loudness. Schomer is not alone in noting the significance of this “compression of dynamic range” at low frequencies. For example, Zwicker and Fastl (1999, p.204) comment on the increasing shallowness of low-frequency noise contours with increasing level; Fidell, Silvati and Pearsons (2002) invoke the same phenomenon as the origin of the rapid growth of annoyance with level of impulsive sounds with predominantly low-frequency content; Kirk and Møller cited the phenomenon as the basis for the sensitive dependence of annoyance on sensations of low-frequency loudness. Møller and Pedersen (2004) likewise note that very low-frequency sounds which are “inaudible to some people may be loud to others.”

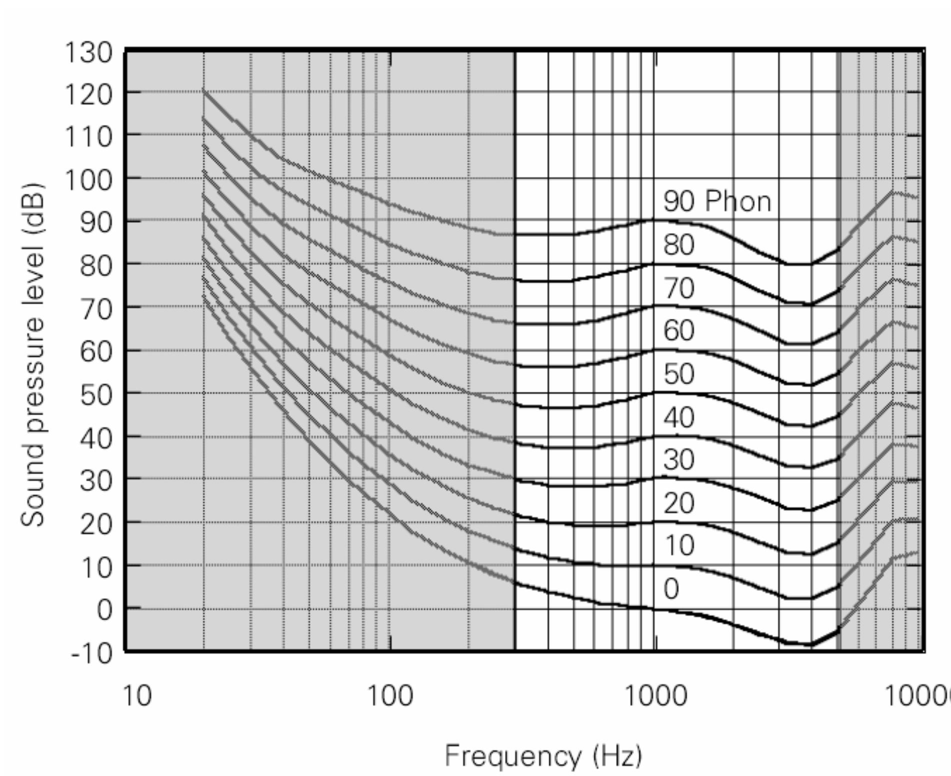

Figure 79: Equal loudness level contours from ISO 226-1987 (from Schomer, 2004, Figure 1) Changes in loudness are closely proportional to changes in sound pressure level only in the unshaded frequency region.

6.4.14 Schust (2004)

Schust’s review focuses initially on low-frequency hearing thresholds. His summary of these effects adds only modestly to those of earlier reviews. He does, however, briefly note a single instance (Doroshenko and Stepchuk, 1983) of a permanent hearing impairment in compressor operators, arguably associated with the presence of infrasonic exposure at levels as high as 119 dB. Schust concludes that there is “little need for further scientific research” on infrasound-induced TTS.

After a discussion of several findings concerning non-specific vascular, respiratory, endocrine, balance, and visual effects of infrasonic exposure, Schust reviews a set of empirical studies (including those of Slarve and Johnson, 1975; Harris and Johnson, 1978; Verzini, Skarp, Nitardi, and Fuchs, 1999, Ising, 1980, Landstrom and Pelmear (1999), and Persson Waye, Bengtsson, Rylander, Hudklebridge, Evans, and Chow, 2002). Schust notes that infrasound-related complaints (of vibration sensations, inability to concentrate, pressure in the ears, etc.) seem to occur at levels about 20 dB greater than absolute hearing sensitivity thresholds.

6.5 Relevance of ride comfort literature

Researchers at NASA LaRC conducted simulator and other studies on aircraft ride comfort in the 1970s and1980s in which they developed a discomfort index for aircraft crew members (*cf*. Leatherwood *et al.,* 1984). The frequency range of concern for noise levels in these studies did not extend to very low or infrasonic frequencies, and hence, is not directly pertinent to tiltrotor applications.

Further, as Conner (1980) points out, measures of ride comfort agree poorly with passenger willingness to travel repeatedly, particularly for short trips in high flight frequency settings (*e.g.*, city-center to city-center business travel), where schedule convenience and total time in transit apparently outweigh concerns about short-term comfort.

6.6 Contributions of secondary emissions to annoyance with low-frequency noise

The annoyance of rattle induced by low-frequency excitation of residences has been studied in both laboratory and field settings, with mixed findings. Two NASA-sponsored studies (Cawthorn *et al.*, 1978; and Fields and Powell, 1987) found no evidence of increased annoyance of aircraft overflights due to noise-induced rattle. Powell and Shepherd (1987) conjecture that the lack of increased annoyance in the magnitude estimation study of Cawthorn *et al*. (which added sounds of rattling glassware to much louder aircraft overflight noise) was not particularly annoying "because the glassware did not belong to the test subjects", and that they were therefore "not annoyed by the possibility of damage."

A delayed self-report (social survey) study of annoyance associated with controlled helicopter overflights conducted by Fields and Powell (1982) also found no increment in annoyance associated with presumed rattling, although slant range was taken as a surrogate for rattle, and no empirical confirmation of the presence or absence of rattle was attempted. Another controlled exposure study in a field setting conducted by Schomer and Neathammer (1987), on the other hand, found strong evidence of incremental annoyance associated with empirically verified rattling. Schomer and Neathammer solicited immediate annoyance judgments of the annoyance of controlled helicopter flights from 201 test participants. They report effects as great as 12 to 20 dB between the annoyance of flights accompanied by "little" and high levels of vibration and rattle with respect to the annoyance of flights unaccompanied by rattle.

In a case study reported by Siskind (1987), rattle and vibration produced by airborne low-frequency energy from demolition of explosives caused concerns about structural damage among residents of nearby homes. A laboratory study by Fidell *et al*. (2002b) found that the judged annoyance of recordings of aircraft ground operations with rattle were notably greater than those of the same recordings without rattle. The findings of other studies of the annoyance of rattle are described in Sections 6.3.1 through 6.3.3 of this report.

7. APPENDIX B: TABULAR SUMMARIES OF REPORTED EFFECTS OF INFRASOUND AND LOW-FREQUENCY NOISE ON INDIVIDUALS

7.1 Summary of auditory effects

Table 10 summarizes reports of positive laboratory findings on auditory, health and safety effects at specific frequencies and sound pressure levels. The table columns display five categories of effect, from audibility to tolerability, with three intermediate categories (pressure in the ears, temporary threshold shift, and aural pain) between these extremes. The rows are ordered first by test frequency, and within frequency by sound level. For a given frequency the highest sound levels are shown first, and the lowest ones shown last. In some instances a range of sound levels was tested, and in these cases the table ranking is based on the highest level tested.

Unless otherwise noted, test signals consisted of fixed-frequency sinusoids. The other stimuli were either broadband noise (BB Noise) with the spectral content peaking at a specific frequency, band-limited noise (BL noise) that was wider than one-third octave and also with a pronounced spectral peak, or narrow band noise (NB noise) where the noise was also bandwidth-limited and one-third octave in width.

Some researchers tested at frequencies higher than 100 Hz. These results are not shown in the table since they fall outside the present area of interest.

Note that all frequencies and sound pressure levels cited are approximate due to measurement and reporting uncertainties. Further, some reports of effects are derived from studies with small numbers of test participants, and may not be replicable.

Table 10: Summary of reported auditory and health/safety effects

FREQUENCY (Hz)	SOUND LEVEL (dB)	HEARING THRESHOLD	PRESSURE ("FULLNESS") IN EARS	TEMPORARY THRESHOLD SHIFT	AURAL PAIN	MAXIMUM TOLERABLE LEVEL
1	160				von Gierke & Nixon (1976)	
	151		Mohr *et al*., 1965			
	145					von Gierke & Ward, 1991 (1 hour)
	144		Slarve & Johnson, 1975			
	136					von Gierke & Ward, 1991 (8 hours)
	130	May, 1978				
2	142-149		Mohr *et al*., 1965 (NB noise)			
	144		Slarve & Johnson, 1975			
	125	Yeowart *et al*., 1967				
	120	Yeowart & Evans, 1974				
	110	Nagai *et al*., 1982				
3	151		Mohr *et al*., 1965 (NB noise)			
	122	Whittle *et al*., 1972				
	121	Yeowart *et al*., 1967				
	110	Nagai *et al*., 1982				

FREQUENCY (Hz)	SOUND LEVEL (dB)	HEARING THRESHOLD	PRESSURE (“FULLNESS”) IN EARS	TEMPORARY THRESHOLD SHIFT	AURAL PAIN	MAXIMUM TOLERABLE LEVEL
4	144		Slarve & Johnson, 1975			
	118	Yeowart *et al*., 1967				
	112	Yeowart & Evans, 1974				
	108	Watanabe & Møller, 1990				
	108	Landstrøm *et al*., 1983				
5	160				von Gierke & Nixon (1976)	
	150		Mohr *et al*., 1965			
	138					von Gierke & Ward, 1991 (1 hour)
	129					von Gierke & Ward, 1991 (8 hours)
	110	Yeowart & Evans, 1974; Watanabe *et al*.,1993; Yeowart *et al*., 1967				
	108	Nagai *et al*., 1982				

FREQUENCY (Hz)	SOUND LEVEL (dB)	HEARING THRESHOLD	PRESSURE ("FULLNESS") IN EARS	TEMPORARY THRESHOLD SHIFT	AURAL PAIN	MAXIMUM TOLERABLE LEVEL
6	146-152		Mohr *et al*., 1965 (NB noise)			
	150		Mohr *et al*., 1965			
	144		Slarve & Johnson, 1975			
	110	Watanabe *et al*.,1993; Yeowart *et al*., 1967				
	106	Yeowart & Evans, 1974; Whittle *et al*., 1972; Landstrøm *et al*., 1983				
	105	Landstrøm *et al*., 1983				
8	145		Mohr *et al*., 1965			
	126-144		Slarve & Johnson, 1975			
	105	Yeowart *et al*., 1967				
	104	Watanabe *et al*.,1993;				
	100	Watanabe & Møller, 1990				
	98	Yamada *et al*., 1980				

FREQUENCY (Hz)	SOUND LEVEL (dB)	HEARING THRESHOLD	PRESSURE ("FULLNESS") IN EARS	TEMPORARY THRESHOLD SHIFT	AURAL PAIN	MAXIMUM TOLERABLE LEVEL
10	150					Mohr *et al.*, 1965 (with hearing protection, from 1 – 100 Hz)
	145		Mohr *et al.*, 1965			
	144		Slarve & Johnson, 1975			
	140			Alford *et al.*, 1966; Jerger *et al.*, 1966 (10-20 dB TTS following 3 min exposures between 2- 12 Hz)		
	135					von Gierke & Ward, 1991 (1 hour)
	130		Karpova *et al.*, 1970; Nixon & Johnson, 1973; Mohr *et al.*, 1965			
	126					von Gierke & Ward, 1991 (8 hours)
	100	Yeowart *et al.*, 1967				
	99	Inukai, Taya, & Yamada, 2005				
	98	Watanabe & Møller, 1990				
	94	Yamada *et al.*, 1980				

FREQUENCY (Hz)	SOUND LEVEL (dB)	HEARING THRESHOLD	PRESSURE ("FULLNESS") IN EARS	TEMPORARY THRESHOLD SHIFT	AURAL PAIN	MAXIMUM TOLERABLE LEVEL
12.5	147-151		Mohr *et al*., 1965 (NB noise)			
	144		Slarve & Johnson, 1975			
	140		Mohr *et al*., 1965			
	91	Inukai, Taya, & Yamada, 2005				
16	139		Slarve & Johnson, 1975			
	88	Inukai, Taya, & Yamada, 2005				
20	140				von Gierke & Nixon (1976)	
	135		Slarve & Johnson, 1975			
	132					von Gierke & Ward, 1991 (1 hour)
	123					von Gierke & Ward, 1991 (8 hours)
	88	Yeowart & Evans, 1974				
	84	Nagai *et al*., 1982				
	82	Inukai, Taya, & Yamada, 2005				
	79	Lydolf & Møller, 1997				

FREQUENCY (Hz)	SOUND LEVEL (dB)	HEARING THRESHOLD	PRESSURE (“FULLNESS”) IN EARS	TEMPORARY THRESHOLD SHIFT	AURAL PAIN	MAXIMUM TOLERABLE LEVEL
25	140-150		Mohr *et al*., 1965			
	142				Mohr *et al*., 1965 (NB noise)	
	132		Slarve & Johnson, 1975			
	75	Inukai, Taya, & Yamada, 2005				
31.5	67	Inukai, Taya, & Yamada, 2005				
	143		Mohr *et al*., 1965 (NB noise)			

FREQUENCY (Hz)	SOUND LEVEL (dB)	HEARING THRESHOLD	PRESSURE ("FULLNESS") IN EARS	TEMPORARY THRESHOLD SHIFT	AURAL PAIN	MAXIMUM TOLERABLE LEVEL
40	150					Mohr *et al*., 1965 ("subjective tolerance limit", 40 – 100 Hz)
	144				Mohr *et al*., 1965 (NB noise)	
	139-144		Mohr *et al*., 1965 (NB noise)			
	74	Okai *et al*., 1980				
	66	Nagai *et al*., 1982				
	64	Watanabe *et al*.,1993				
	60	Yamada *et al*., 1980; Inukai, Taya, & Yamada, 2005				
	58	Whittle *et al*., 1972				
	50	Lydolf & Møller, 1997				

FREQUENCY (Hz)	SOUND LEVEL (dB)	HEARING THRESHOLD	PRESSURE ("FULLNESS") IN EARS	TEMPORARY THRESHOLD SHIFT	AURAL PAIN	MAXIMUM TOLERABLE LEVEL
50	153					Mohr *et al*., 1965 (voluntary tolerance limit)
	65	Okai *et al*., 1980				
	55	Yeowart *et al*., 1967; Yamada *et al*., 1980				
	54	Watanabe *et al*.,1993				
	51	Inukai, Taya, & Yamada, 2005				
	46	Lydolf & Møller, 1997				
	44	Yeowart & Evans, 1974				
60	154					Mohr *et al*., 1965 (voluntary tolerance limit)
63	45	Inukai, Taya, & Yamada, 2005				
70	150					Mohr *et al*., 1965 (voluntary tolerance limit)

7.2 Cognitive and other extra-auditory effects

Table 11 summarizes laboratory findings on reported cognitive and other extra-auditory effects of various combinations of frequency and sound level amplitude. The table columns display five categories of effect, from loudness to blurred vision, with three intermediate categories (annoyance, interference with task performance, and visceral sensations) between these extremes. Visceral sensations include chest wall vibration, hypopharyngeal fullness (gagging), and subcostal discomfort due to excitation of resonances in abdominal and thoracic cavities.

The rows are ordered first by test frequency, and within frequency by sound level. For a given frequency the highest sound levels are shown first, and the lowest ones shown last. In some instances a range of sound levels was tested, and in these cases the table ranking is based on the highest level tested.

Unless otherwise noted, test signals consisted of fixed-frequency sinusoids. The other stimuli were either broadband noise (BB Noise) with the spectral content peaking at a specific frequency, band-limited noise (BL noise) that was wider than one-third octave and also with a pronounced spectral peak, or narrow band noise (NB noise) where the noise was also bandwidth-limited and one-third octave in width.

Some researchers tested at frequencies higher than 100 Hz. These results are not shown in the table since they fall outside the frequency range of present interest.

Note that all frequencies and sound pressure levels cited are approximate due to measurement and reporting uncertainties. Further, some reports of effects are derived from studies with small numbers of test participants, and may not be replicable.

Table 11: Summary of cognitive and other extra-auditory effects

FREQUENCY (Hz)	SOUND LEVEL (dB)	LOUDNESS	ANNOYANCE	INTERFERENCE WITH TASK PERFORMANCE	VISCERAL SENSATION	BLURRED VISION
2	108-123	Kirk & Møller, 1981				
4	120		Møller, Henningsen and Andresen, 1984			
	104-118	Kirk & Møller, 1981				
7	125-142			Harris & Johnson, 1978		
8	108-124		Møller, Henningsen and Andresen, 1984			
	100-118	Kirk & Møller, 1981				
10	120		Inukai, Nakamura & Taya, 2000			
12.5	116		Inukai, Nakamura & Taya, 2000			
16	95-115		Møller, Henningsen and Andresen, 1984			
	90-118	Kirk & Møller, 1981				
	112		Inukai, Nakamura & Taya, 2000			

FREQUENCY (Hz)	SOUND LEVEL (dB)	LOUDNESS	ANNOYANCE	INTERFERENCE WITH TASK PERFORMANCE	VISCERAL SENSATION	BLURRED VISION
20	80-125	Lydolf & Møller, 1997				
	108		Inukai, Nakamura & Taya, 2000			
	56-76		Kelley, 1987 (22 min)			
25	142				Mohr *et al*., 1965 (NB noise)	
	72-130	Lydolf & Møller, 1997				
	104		Inukai, Nakamura & Taya, 2000			
	55-75		Broner & Leventhal, 1983 (BL noise)			
31.5	62-125	Lydolf & Møller, 1997				
	70-113	Kirk & Møller, 1981				
	75-100		Møller, Henningsen and Andresen, 1984			
	100		Inukai, Nakamura & Taya, 2000			
	80		Bradley, 1994 (BB noise)			
35	55-75		Broner & Leventhal, 1983 (BL noise)			

FREQUENCY (Hz)	SOUND LEVEL (dB)	LOUDNESS	ANNOYANCE	INTERFERENCE WITH TASK PERFORMANCE	VISCERAL SENSATION	BLURRED VISION
40	144				Mohr *et al*., 1965 (NB noise)	
	52-120	Lydolf & Møller, 1997				
	96		Inukai, Nakamura & Taya, 2000			
45	153					Mohr *et al*., 1965 (siren)
	55-75		Broner & Leventhal, 1983 (BL noise)			
50	153					Mohr *et al*., 1965 (siren)
	52-118	Lydolf & Møller, 1997				
	92		Inukai, Nakamura & Taya, 2000			
55	55-75		Broner & Leventhal, 1983 (BL noise)			
63	39-115	Lydolf & Møller, 1997				
	55-107	Kirk & Møller, 1981				
	88		Inukai, Nakamura & Taya, 2000			
65	55-75		Broner & Leventhal, 1983 (BL noise)			

FREQUENCY (Hz)	SOUND LEVEL (dB)	LOUDNESS	ANNOYANCE	INTERFERENCE WITH TASK PERFORMANCE	VISCERAL SENSATION	BLURRED VISION
75	150					Mohr *et al.*, 1965 (siren)
	55-75		Broner & Leventhal, 1983 (BL noise)			
80	35-105	Lydolf & Møller, 1997				
	84		Inukai, Nakamura & Taya, 2000			
100	30-107	Lydolf & Møller, 1997				
	80		Inukai, Nakamura & Taya, 2000			

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8. APPENDIX C: RECOMMENDATIONS FOR A CONTROLLED EXPOSURE STUDY OF COMMUNITY RESPONSE TO LOW-FREQUENCY NOISE

8.1 Overall Technical Goal for Controlled Exposure Studies

The goal of the recommended field research is to estimate the prevalence of residential high annoyance with secondary emissions (rattling noises) due to controlled exposure to low-frequency noise resembling, as closely as possible, that of future heavy lift tiltrotors. Details of such a study are described in Sections 8.2 through 8.8. Due to considerable uncertainty about the availability of suitable sites, readily foreseeable pragmatic, ethical, and political concerns, and potential high costs, however, a controlled exposure study is best preceded by one or more feasibility studies, as described below.

8.1.1 Feasibility of helicopter-based simulation of low-frequency tiltrotor noise

An initial feasibility study should investigate the potential use of heavy lift helicopters to generate low-frequency noise similar to that of future large civil tiltrotors. An important part of such a feasibility study would entail discussions with an Institutional Review Board (IRB) about informed consent issues[30]; about the nature of risks of tiltrotor-like rotorcraft operations in residential areas, and of low-frequency noise exposure to public health; and about the ratio of risks to benefits of the intended research. The membership of the IRB would have to include not only technically knowledgeable personnel, but also one or more persons capable of representing general public interests, and of understanding societal benefits of the intended research in regulatory policy matters broader than tiltrotor development.

A hierarchy of community settings in which it would be useful to conduct a controlled exposure study is readily apparent. In order of utility for present purposes, these settings are:

1. Purely residential neighborhoods with negligible prior exposure to aircraft noise;

2. Mixed (residential/commercial/industrial use) urban areas with a greater degree of noise exposure, such as neighborhoods near extant helipads, heavy truck or rail traffic, and/or industrial noise;

3. Mixed residential areas with regular exposure to civil aircraft noise, such as those in the vicinity of general aviation airports; and

4) Residential areas near large civil or military airfields with heavy exposure to aircraft noise, such as military base housing or neighborhoods near runways at larger airports.

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[30] Although it is effectively impossible to obtain informed consent from thousands of residents intentionally exposed to low-frequency noise for participation in a community-wide controlled noise exposure study, it might be possible to substitute the consent of elected local governments for studies in which the public health risks of participation are negligible.

The higher priority settings are those in which intentional tiltrotor-like, low-frequency noise exposure would be only minimally confounded by other noise sources, and could be closely simulated; and in which few complications would impede generalization of findings to the wider urban population.

Of the two most common types of U.S. heavy lift helicopters, use of one (the CH-47) would almost certainly require cooperation by a U.S. Army agency, while use of the other (the S-64) would require expensive leasing arrangements. Some of the difficulties likely to be encountered in operating either a military or civil heavy lift helicopter in residential areas in a manner closely resembling that of future tiltrotors include safety of flight and ground safety concerns; resistance by elected officials to frequent low-altitude flights in residential areas; opposition by airport managements to conducting such operations near their facilities; and identification of a suitable geographic grouping of community areas in reasonable proximity to helicopter operating bases.

The goal of an initial feasibility study is to locate potential venues for a helicopter-based simulation of low-frequency tiltrotor noise, preferably in a community setting lacking other aircraft noise exposure. If no such venues can be found in one of the higher priority settings, the study should be repeated for each of the lower utility settings noted above.

8.1.2 Feasibility of simulator-based controlled low-frequency noise exposure

A contingent feasibility study should be conducted if it is concluded that no suitable venue can be found for a study in which tiltrotor-like low-frequency noise is generated by heavy lift helicopters. The goal of such a second stage feasibility study is to identify potential sites at which a custom-designed, field-portable device (*cf*. Section 5.2.2) can be operated in residential areas. Although such a study would probably entail fewer safety concerns and other constraints, as well as lower costs than a study in which heavy lift helicopters are used to simulate the noise of tiltrotor operations, advance notification and cooperation by local government agencies, citizen activist groups, and/or homeowners' associations remain essential.

8.2 Site Selection

8.2.1 Logistical constraints

For reasons of cost and convenience, proximity to the operating base(s) of the heavy lift helicopters used to simulate the low-frequency noise of large civil tiltrotors may be the major practical constraint on site selection. Communities to be exposed to low-frequency noise will most likely have to be situated no farther than about 15 – 30 minutes of flight time from the base(s) of operations of heavy lift helicopters. For reasons discussed in Section 8.6, several such communities, each a few minutes flying time from one another, are needed to maximize the numbers of homes insonified (and hence, respondents eligible for interview) per flight hour.

8.2.2 Political constraints

Complaints about community exposure to the noise of early morning and late afternoon heavy lift helicopter operations during the course of an intentional exposure study are inevitable. It may also prove necessary to obtain permission to temporarily fence takeoff and landing sites within public facilities (parks, schoolyards, parking lots, building roofs, *etc*.) The cooperation of airport, municipal, and/or county or even state agencies is therefore essential, and must be secured months in advance of the start of the study. At a minimum, local government must be notified in ample time of the goals and schedule of the study, and information about the schedule

of operations must be made available. Some form of *quid pro quo* for exposed communities may also prove necessary to gain the cooperation of local authorities.

A website describing the general nature of the study, and capable of tracking complaints about low-frequency noise exposure during the course of the study, could help to minimize the risk that adverse community reaction could force abandonment of the study.

If expedience dictates that the simulation of tiltrotor applications must be undertaken at an existing airport, efforts should be made to coordinate the operations with airport management. Although airport managements may not have any formal ability to refuse transient operations, they are unlikely to welcome flight activity that they believe may jeopardize airport-community relations.

8.2.3 Background noise constraints

Infrasonic noise measurements should be made to verify that ambient noise levels at frequencies lower than 20 Hz are at least 20 dB lower than those of the intentional noise exposure. Potential sites near power plants, refineries, seaports frequented by large ships, rail and other ventilated tunnels, and other large industrial facilities need to be especially carefully evaluated for operation of machinery that can cyclically produce high levels of infrasound. Such measurements require special purpose instrumentation, including instrumentation-grade, low-frequency microphones and pre-amplifiers, large windscreens, and spectrum analyzers (such as a Larson-Davis 2900) designed to work at frequencies close to DC.

8.2.4 Characteristics of communities likely to be exposed to heavy lift tiltrotor noise

Communities that may eventually be exposed to high levels of low-frequency noise from large civil tiltrotors will generally be located either near existing airports, or in city-center areas. Population densities and cumulative noise exposure levels in such airport and urban areas are likely to be relatively high. To the extent feasible, residential areas to be intentionally exposed to simulated tiltrotor noise in the current field study should be selected with similarly high population densities and noise exposure levels.

8.3 Exposure regimen

Simulated community exposure to low-frequency noise should ideally be designed 1) to last longer than any transient reactions to its onset; 2) to resemble a potential schedule of commercial tiltrotor operations; and 3) to span as great a range of exposure levels as feasible. Some of the implications of these exposure conditions are noted below.

8.3.1 Exposure duration

Although little is known quantitatively about the time constant of community response to noise exposure, a period of at least several weeks must pass before it is plausible to assume that aircraft noise-induced annoyance has asymptoted near steady-state levels (Fidell *et al.,* 1985). Thus, intentional exposure to simulated tiltrotor low-frequency noise should last for at least several weeks – if not longer - prior to interviewing.

8.3.2 Nature of flight operations

The most faithful simulation of low-frequency noise exposure from tiltrotor operations would include an approach from pattern altitude to a landing, followed by an engine shutdown period of 20 – 30 minutes, and a subsequent takeoff. Given 1) the costs of heavy lift helicopter flight time;

2) the need to minimize the number of aircraft required to visit multiple sites within short periods of time (see Section 8.3.3); and 3) potential difficulties in arranging for safe landing areas in residential areas, simulations of tiltrotor operations that do not include landings and takeoffs may prove necessary.

Thus, for example, a reduced-fidelity simulation cycle might include an approach in level forward flight from an assumed pattern altitude (say, 1000' AGL) to a landmark such as a public parking lot; several minutes of hovering flight above the landmark with zero forward airspeed[31]; and a subsequent return to pattern altitude and departure in level flight. The least compelling, but perhaps the most feasible, simulation might consist simply of low altitude, low speed overflights. Since the principal interest is in the effects of low-frequency noise *per se*, care must be taken to avoid rapid ascent/descent flight profiles and the attendant likelihood of BVI noise.[32]

8.3.3 Numbers and times of day of flight operations

Operations of heavy lift civil tiltrotors in commercial passenger service are likely to require balanced numbers of morning and late afternoon/evening flights, for reasons of both air transportation demand, and for efficient utilization of expensive aircraft. Typical business demand for commercially viable, city-pair air transportation requires at least two early morning departures in each direction, and at least one pair of late afternoon return flights. From the perspective of residents near an urban tiltrotor operating area, this implies a minimum of eight daily operations: one pair of morning takeoffs and landings, and one pair of afternoon/evening takeoffs and landings.

Eight operations per day thus constitutes the smallest useful number of simulated tiltrotor operations for present purposes. A schedule for a small (~200 passenger-roundtrips per weekday), business travel-dominated city-pair market might therefore resemble that shown in Table 12.

Table 12: Typical schedule for low level of service

	7:00 - 8:00 AM	8:00 – 9:00 AM	5:00 - 6:00 PM	6:00 – 7:00 PM	TOTAL
DEPARTURES	1	1	1	1	4
ARRIVALS	1	1	1	1	4

As suggested in Table 13, a city-pair market that could support about 400 business travelers per weekday would require at least 16 operations, and generate 3 dB greater exposure to low-frequency noise.

[31] Safety of flight concerns will require maintenance of a hover altitude no lower than required for a successful auto-rotational landing. This altitude will vary both with helicopter type and pilot experience, but is unlikely to be lower than a few hundred feet. The rotor wash from a lower altitude hovering heavy lift rotorcraft would in any event pose ground level risks of hazardous flying debris.

[32] As time and budget permit, a secondary study of the additional effects of BVI noise on annoyance could be conducted at the conclusion of the initial study. A second round of interviews could be scheduled to assess whether and how much BVI noise affects reactions to low-frequency noise.

Table 13: Typical schedule for moderate level of service

	7:00 - 8:00 AM	8:00 – 9:00 AM	5:00 - 6:00 PM	6:00 – 7:00 PM	TOTAL
DEPARTURES	2	2	2	2	8
ARRIVALS	2	2	2	2	8

Although more than one flight crew might be necessary to support these schedules, a single helicopter based within 15 - 30 minutes flying time from a community to be experimentally exposed to landing and takeoff noise would probably suffice, and still leave ample time for routine maintenance between morning and afternoon operations. Another doubling of this flight schedule (to 32 operations per day, capable of serving city-pair markets supporting ~800 roundtrip passengers), however, would probably require two or more helicopters and perhaps as many as four flight crews.

8.3.4 Cost implications

Unless a military agency donates flight time, the purchase of heavy lift helicopter flight hours will be a major cost element of this study. Since costs will be highly sensitive to logistical details (such as the distance from the helicopter's base to selected communities, flight and maintenance crew field subsistence arrangements, and the like), it is not possible to closely estimate study costs.

For purposes of producing rough order-of-magnitude estimates of the cost of the flying time required to meet the exposure schedule seen in Table 12, however, it can be assumed that six hours a day of flight time will be required for 30 days. If the effective hourly operating cost for a single heavy-lift helicopter and crew were as *little* as $4,000, the requisite 180 flight hours would cost about $720,000. The +3 dB exposure schedule of Table 13 would not necessarily cost proportionately more in flying time, but could nonetheless be considerably more expensive. Yet another doubling in noise exposure levels (to yield a +6 dB exposure condition) would very likely increase flight time costs above $1,500,000.

8.4 Interviewing Method

Computer-assisted telephone interviewing is strongly recommended. Telephone interviews are better suited and more cost-effective for rapid collection of modest amounts of specific information than in-person (face-to-face) interviews. Telephone interviewing by centrally supervised, trained and experienced interviewers also supports higher response rates and tighter control over administration of questionnaires than postal surveys.

8.5 Questionnaire construction

A brief, structured questionnaire introduced as a study of neighborhood living conditions and narrowly focused on soliciting reactions to low-frequency aircraft noise exposure is preferred. The wording of questionnaire items should closely resemble that of prior questionnaires concerning community noise impacts, as should the wording of closed-category response scales. To preserve close comparability of findings with those of prior opinion surveys about the annoyance of aircraft noise-induced rattle such as those of Fidell *et al.* (1999) and Fidell *et al.* (2002), the order and wording of questionnaire items should closely resemble those shown in

Figure 80.[33] Even if it proves necessary to add additional questions to the interview (for example, to collect extraneous information as an inducement to encourage local government cooperation), average interview times should be kept under five minutes.

ITEM 1.	About how long have you lived at [street address]?
ITEM 2.	What do you like best about living conditions in your neighborhood?
ITEM 3.	What do you like least about living conditions in your neighborhood?
ITEM 4.	Would you say that your neighborhood is quiet or noisy? *SKIP TO ITEM 5 if response to Item 4 was "quiet."*
ITEM 4A.	Would you say that your neighborhood is slightly noisy, moderately noisy, very noisy, or extremely noisy?
ITEM 5.	While you're at home are you bothered or annoyed by street traffic noise in your neighborhood? *SKIP TO ITEM 6 if response to Item 5 was "no."*
ITEM 5A.	Would you say that you are slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by street traffic noise in your neighborhood?
ITEM 6.	While you've been at home over the last few weeks have you been bothered or annoyed by aircraft noise? *SKIP TO ITEM 7 if response to Item 6 was "no."*
ITEM 6A.	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by aircraft noise while you've been at home over the last few weeks?
ITEM 7.	Have aircraft made vibrations or rattling sounds in your home during the last few weeks? *Conclude interview if response to Item 7 was "no."*
ITEM 8.	Have you been bothered or annoyed by these vibrations or rattling sounds in your home during the last few weeks? *SKIP TO ITEM 9 if response to Item 8 was "no."*
ITEM 8A.	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by vibrations or rattling sounds in your home over the last few weeks?
ITEM 9.	About how often have noticed vibrations or rattling sounds in your home made by aircraft over the last few weeks?
ITEM 10.	What sorts of things vibrate or rattle in your home?

Figure 80: Suggested wording of core questionnaire items

[33] Even though vibration and rattling are cause and effect, the terms may be interchangeable in colloquial use. If it is of practical importance to clearly distinguish between the terms, it may be useful to reconsider the relevant questionnaire wording.

8.6 Sampling plan

Adequate numbers of interviewing sites, exposure zones within sites, and eligible respondents per exposure zone and site are required for reliable and interpretable results. More specifically, sites must be selected at which sufficient interviews can be completed with respondents who will be exposed to a useful range of low-frequency noise levels. Some simplifying assumptions made for initial planning purposes are as follows:

1) the population density at sites to be exposed to low-frequency noise is on the order of 5,000 people/mi^2 (about 1900/km^2), the approximate median density in U.S. urban areas;
2) households are uniformly distributed geographically with respect to the helicopter landing pad;
3) the number of residents per household is approximately 3.5, yielding approximately 1425 households/mi^2 (550/ km^2);
4) one adult household member is eligible for interview; and
5) the interview completion rate will be approximately 70%.

Sampling frames should be developed of all telephone-subscribing households within three radii of each landing area. In each residential area to be insonified, concentric radius samples should be drawn at ranges corresponding to nominal 6 dB differences in low-frequency sound pressure levels. At the very low frequencies of interest, propagation effects other than inverse square (20 log D) spreading may be safely ignored. Thus, if the inner radius includes all households within 500 m of a landing site, the intermediate radius should be 1 km, and the outermost radius 2 km.

This sampling scheme yields three noise exposure zones (an innermost circle, an intermediate ring, and an outer ring), as shown in Figure 81. Within each zone, low-frequency noise levels vary by approximately ± 3 dB, while across the three zones, the absolute range of low-frequency noise levels is 18 dB. If the nominal low-frequency source level at the central helicopter landing pad is 120 dB, then low-frequency noise levels at households within the inner radius should ideally range from 114 to 120 dB. At households within the intermediate ring, low-frequency noise levels should range from 108 to 114 dB, and at households within the outer ring, low-frequency noise levels should range from 102 to 108 dB.

Given the simplifying assumptions outlined above, the numbers of respondents eligible for interview should be roughly 330 in the innermost ring; about 900 in the intermediate ring; and about 3900 in the outermost ring. These assumed conditions are of course idealized; under a more realistic set of assumptions (*i.e.*, non-homogeneous geographic distributions of housing, lower population densities, and/or fewer residents per household), each of these figures must be reduced by at least half.

If a landing pad central to a residential area is not feasible, the estimates of available numbers of completed interviews should be reduced further yet. For example, if the only suitable landing area near a residential neighborhood is on paved area adjacent to a fixed base operator on one side of an airport runway, interviewing might have to be restricted to a sector of at most half of the area of the sampling circle.

For planning purposes, it is therefore unrealistic to count on more than about 150 completed interviews within the highest (innermost in Figure 81) exposure level zone at a given site. To acquire 400-500 interviews in the highest level exposure zone (and hence, 95% confidence intervals on the order of ± 5 % or smaller around estimates of the proportion of respondents highly annoyed by low-frequency noise effects), it may be necessary to combine interview responses across similar exposure levels at three or more exposure sites.[34]

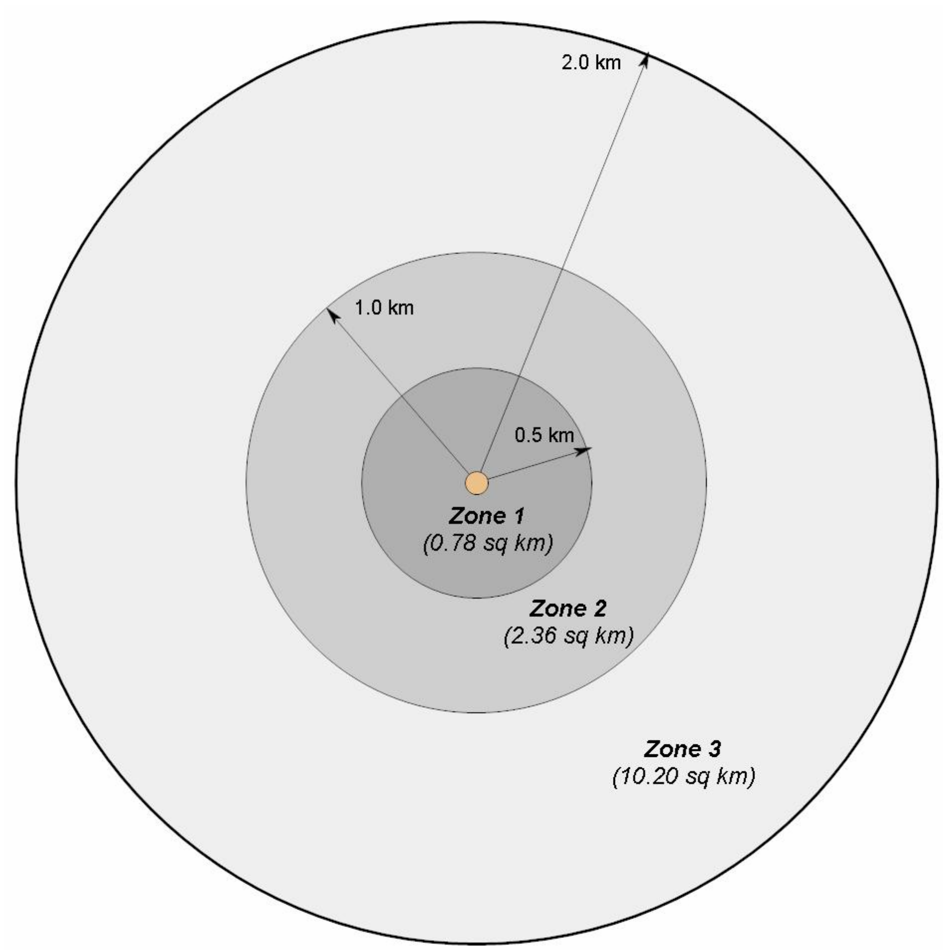

Figure 81: Noise exposure zones for a landing area central to a residential area.

Attempts should be made to exhaust the entire sampling frame for the highest level exposure zones at all sites with as many as ten callbacks. If the numbers of eligible respondents in the intermediate and lower exposure zones permit, fractions of the eligible households in the sampling frames may be randomly selected for interviewing.

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[34] Even though a smaller number of exposure sites might suffice to yield ample numbers of completed interviews within the lower exposure level zones, the per-site costs will greatly exceed the per-interview costs, so interviewing should be conducted in all three exposure zones at all exposure sites. Complete interviewing at multiple sites will also permit at least a partial analysis of site-specific (as opposed to level-specific) differences in response patterns.

Site-specific estimates of numbers of respondents eligible for interview at varying distances (*i.e.*, exposure levels) from the helicopter operating area must ultimately be undertaken as part of the site selection process.

8.7 Noise exposure monitoring

The primary purposes of exposure monitoring are to confirm the levels of controlled, episodic low-frequency noise events, and to measure the ambient conditions at each of the respondent locations. Since respondents near the landing pad will view the sound source at moderate to high angles of elevation with respect to the horizon, overground propagation effects are unlikely to appreciably influence the low-frequency sound pressure levels to which they are exposed. The grazing incidence low-frequency exposure of respondents at greater distances from the landing pad, however, may be affected by overground propagation effects. Provision must be made to acquire the information needed to account for such effects during data analysis.

8.7.1 Sound level monitoring

The minimal monitoring requirement is one logging sound level meter per exposure zone at each site. This monitor should be capable of automated (unattended) measurements of one-third octave band sound pressure levels at all frequencies between 6.3 Hz and 10 kHz, at a rate no slower than one spectrum per second, 24 hours per day. Noise levels should be monitored with outdoor ground plane microphones protected from wind noise artifacts with a windscreen, as illustrated in Figure 82.

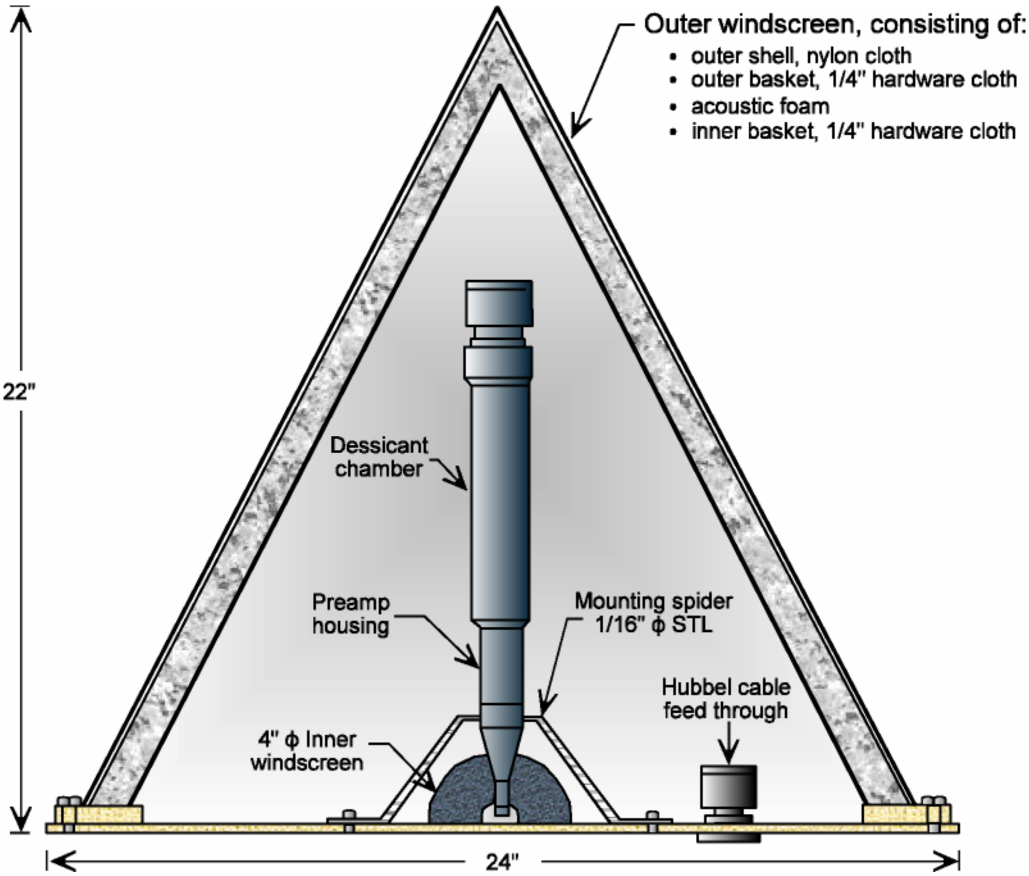

Figure 82 Windscreen and ground plane microphone for low-frequency noise monitoring

If the noise monitoring budget permits, two monitors per exposure zone are preferable. One monitor should be positioned upwind and one downwind from the landing site with respect to the prevailing seasonal wind at the site. No indoor measurements of either sound or vibration levels are required. It has been amply demonstrated (*e.g.*, Hogdon *et al*. 2007) 1) that structureborne vibration levels are ungeneralizably sensitive to accelerometer placement, and that audible rattle can occur at levels lower than those needed to produce sensible structural vibration; and 2) that typical residences are effectively acoustically transparent at very low frequencies.

8.7.2 Wind monitoring

Two anemometers should be installed on each of two 10-meter masts. The minimal detectable wind speed must be no greater than 0.5 miles per hour (mph), or 0.22 meters per second (m/s). Adequate sound ray bending to nullify the sound attenuating barrier effect of single and two story dwellings occurs at approximately 2 mph (0.9 m/s). The data logging device must be capable of acquiring a speed and direction pair every 2 seconds to permit subsequent calculation of means and variances of wind speed distributions over 0.5 to 1 minute periods.

8.7.3 Temperature monitoring

The minimum temperature monitoring requirement is two temperature sensor pairs per site, mounted on the wind monitor masts at 5 and 10-meter heights above ground level. These sensors should have an accuracy of at least 0.5 degrees Fahrenheit (0.25 degrees Celsius). The

data logging device must record the temperature pair values at one-minute intervals. The temperature information is needed to assess temperature inversions and the potential for sound ray bending over barriers.

8.8 Data Analysis

8.8.1 Analysis of interview responses

The primary goal of the analysis of responses to the questionnaire is to estimate the prevalence of a consequential degree of annoyance with rattle and vibration due to simulated tiltrotor low-frequency noise. This requires, at a minimum, determining the proportion of respondents describing themselves as “very” or “highly” annoyed in Item 8A of the sample questionnaire of Figure 80. These proportions should be plotted against the low-frequency sound levels calculated for the exposure zones in which respondents describing themselves as “very” or “highly” annoyed by rattle. These proportions should be plotted against the low-frequency sound levels calculated for the exposure zones in which respondents live and combined with prior published data (as seen in Figure 70) to update a dosage-effect relationship between low-frequency sound levels and annoyance due to rattle.

Additional analyses should also be conducted to confirm the validity, reasonableness and consistency of the findings with those of prior findings. For example, interview completion rates should be calculated, and the prevalence of annoyance due to street traffic and aircraft noise should be compared with that predicted by the FICON (1992) relationship.

8.8.2 Analysis of monitored noise levels

The major goals of the analysis of monitored noise levels are 1) to estimate low-frequency sound levels at each of the monitoring sites, and 2) to confirm that scheduled helicopter operations were the predominant source of low-frequency noise levels at each site. DNL values should also be calculated for each exposure zone for time periods when helicopter noise was both present and absent.

Additional sound level metrics to be calculated include A-, C-, and G-weighted mean levels, as well as several variants of low-frequency sound level metrics. The purpose of calculating low-frequency sound levels is to determine which one(s) of these single-event measures correlate most highly with the prevalence of rattle-induced annoyance. Potential analysis bandwidths are shown in Table 14. The bands are all constructed from one-third octave values. Bandwidths of one, two and three octaves are shown. The two-octave analysis band used in previous low-frequency studies (*i.e.,* the independent variable in Figure 70) is shaded in blue.

Table 14: Possible low-frequency sound level metric frequency ranges

Analysis Bandwidth	No. of Bands	One-third Octave Bands Included in Each Analysis Bandwidth						
		Analysis Bandwidth Center Frequency (Hz)						
		8	11.3	16	22.4	31.5	44.5	63
1 octave	3	6.3-10		12.5-20		25-40		50-80
2 octave	6		6.3-20		12.5-40		**25-80**	
3 octave	9			6.3-40		12.5-80		

Single event analyses should also be conducted, based on estimates of the sound levels associated with each intentional low-frequency noise. These sound levels will be adjusted for "excess" ground attenuation and diffraction within quadrants of each exposure zone, as inferred from the temperature and wind measurements.

9. APPENDIX D: RECOMMENDATIONS FOR FEASIBILITY ANALYSIS AND DEVELOPMENT OF PROTOTYPE ROTOR NOISE SIMULATOR

9.1 Overall Technical Goals for Feasibility and Prototype Development Studies

The goal of this study is to develop a special purpose, truck-portable, and relatively inexpensive device intended to produce high intensity, very low-frequency acoustic signals similar to those emitted by a large civil tiltrotor aircraft (*cf*. Section 1.3) for use in conjunction with social surveys of community response to tiltrotor-like noise. The device must be highly reliable, require little maintenance, and be capable of safe, reliable and (preferably) unattended automatic operation in field settings.

Since the intended use of the device is to produce airborne acoustic energy that will excite neighborhood-wide secondary emissions inside residences, the device must generate and radiate high levels (on the order of 130 - 140 dB) of very low-frequency acoustic energy under free field conditions at a fundamental frequency of approximately 10 Hz. The desired device is not a general purpose, broadband generator of acoustic energy, but rather a source optimized to produce only a narrow range of tiltrotor-like low-frequency signals.

Some capability for managing the relative amplitude of harmonics is also desirable, although not critically important. Since the direct acoustic output of the device is not intended to support detailed psychoacoustic studies, it need not produce waveshapes that closely resemble those of helicopter rotors. Nonetheless, ability to at least grossly control the shape of individual pressure pulses would be a useful feature.

Preliminary analyses (*cf*. Section 5.2.2) suggest that the two most feasible mechanisms for the desired device are 1) a caged whirl stand for a single, counter-weighted rotor, and 2) a custom-designed, low pressure/high volume infrasonic siren. The effort described below should be undertaken to determine which of the two devices is preferable for present purposes; to complete a detailed system design; and to fabricate and demonstrate a scale model prototype system.

9.2 Study Elements

The basic elements of the suggested study are described below.

9.2.1 Detailed analyses of the suitability of whirl stand and siren-based devices

Detailed assessments should be undertaken of the relative suitability for present purposes of the two custom-designed devices described above as sources of high intensity, very low-frequency pulse trains similar to those produced by tiltrotor aircraft. These paper-and-pencil exercises should identify the main design parameters of the devices, and estimate the source levels, spectral content, and directivity of noise emissions that they could produce.

The analyses should also estimate the scalability and range of noise emissions of the two devices, and the degree to which they could be tailored to resemble the spectral and phase characteristics of tiltrotor emissions. The analyses should also compare predicted development

and fabrication risks, schedules and costs, and assess the convenience and suitability of operation of each device in field settings.

The deliverable product of this study phase is a detailed interim report describing the relative advantages and disadvantages of each as a portable simulator of tiltrotor noise emissions, and justifying the selection of one of the mechanisms as more suitable than the other for present purposes.

9.2.2 Development of technical specifications for recommended device

Complete system specifications shall be produced for the recommended device. If the whirl stand is the preferred device, the necessary rotor shape, tip speed, and other dimensions shall be specified, as well as any variants of these factors that may be useful to simulate variant tiltrotor designs. If the low pressure/high volume siren is the preferred device, calculations shall be performed to establish duct and outlet configurations and dimensions, required airflow rates and volumes, and all other operational parameters.

For either device, preliminary mechanical drawings shall be produced in sufficient detail to illustrate all principles and modes of operation, and to guide construction of a prototype system. The specifications must also address system power requirements, safety provisions, and all other operational characteristics of the device.

The deliverable product of this study phase is a second interim report containing technical specifications and drawings adequate to guide development of a prototype device.

9.2.3 Construction and demonstration of a functional prototype

If the technical specifications, mechanical design, and development risks are considered acceptable, a functional prototype shall be fabricated. The prototype device need not be fully ready for deployment in field settings (that is, fully transportable, self-powered, and packaged for field use), but must nonetheless be capable of demonstrating that it meets basic design specifications. A reduced scale model of the device is acceptable if it can be demonstrated with high confidence that a full-scale version of the device will meet all of the technical specifications.

An acoustic measurement plan must be prepared prior to the start of prototype construction to quantify the noise emissions of the device. The latter plan must describe the number, nature, and type of instrumentation; measurement distances and locations; analysis procedures; and all other relevant conditions of an empirical demonstration of the noise emissions of the prototype system. The prototype device shall be operated for at least two hours per day, five days per week, for two consecutive weeks. During this time, the acoustic output of the prototype system shall be measured and documented in accordance with the acoustic measurement plan.

The deliverable products of this study phase shall be

1) A set of “as-built” mechanical drawings fully documenting the construction of the prototype device

2) A technical report describing the results of the acoustic measurements of the device’s noise emissions; and

3) The prototype device itself.

9.3 (OPTIONAL) Production of a field-ready simulator system

Assuming that the acoustic performance of the prototype system meets specifications, a full-scale simulation device capable of stand-alone operation shall be fabricated and packaged for field use. The field-ready system should be either built into or transportable within a single, conventional eight wheel semi-trailer body (~2.6 m high, 4 m wide, and 16 m long). The field-ready system shall include all external power sources and/or other support equipment.

The field-ready system should include full written documentation (in both hardcopy and computer-readable form) of operation and maintenance procedures. If the system requires on-site construction (for example, of a safety cage for a whirl stand), full instructions for the assembly and disassembly of such construction shall be provided as well.

10. APPENDIX E: RECOMMENDATIONS FOR AN ADVENTITIOUS FIELD STUDY OF COMMUNITY REACTION TO LOW-FREQUENCY NOISE EXPOSURE

10.1 Overall Technical Goals for Adventitious Exposure Study

The goals of this research effort are 1) to assess the feasibility of conducting social surveys of residential annoyance induced by low-frequency helicopter noise as similar as possible in character to that expected to be produced by large civil tiltrotor operations, and 2) to conduct such surveys at as many sites as are judged suitable for this purpose (if any), as resources permit.

10.2 Site Requirements

Preferred sites are those at which sizable populations (at least hundreds of households) are exposed to reasonably frequent daily heavy-lift helicopter arrival and departure activity. The population at each site must be sufficient for development of dose-response relationships with minimum uncertainty, and for comparisons of annoyance prevalence rates across sites.

Residential areas that are regularly exposed to appreciable helicopter landing and takeoff noise tend to be located either on or near military bases, or in the vicinity of small airports or special purpose, limited-use helipads. Populations residing in military family housing, however, differ from the general urban population in several ways, including age, economic dependence on military employment, and expected duration of residence. Residents of military family housing also do not own their homes, are self-selected for tolerance to sacrifices in quality of life associated with a military lifestyle, and may well be adapted to helicopter noise.

Multiple sites are desirable to ascertain the extent of any differences in annoyance associated with exposure conditions, as well as any response biases of the exposed populations.

10.3 Site Identification Phase

Many urban and suburban residential areas are regularly exposed to noise from helicopter operations miles from helicopter bases of operation. Noise exposure in cruising overflight is not of particular interest for present purposes, however, for two reasons. First, *en route* tiltrotor noise is not expected to create high levels of infrasound in the frequency range most likely to excite resonances in typical home construction (*cf*. Section 1.5.3). Second, the characteristics of *en route* helicopter noise – particularly duration, level, and low-frequency spectral content - do not closely resemble those of low-frequency tiltrotor noise in hover and slow forward flight.

Helicopter operations at general aviation airports, as well as those at special purpose helipads located in residential areas (including some associated with hospitals, traffic observation, and fire and police facilities), are typically more limited in scope than those at military training bases. To the extent that local land use planning has been successful in limiting community encroachment on airports, they are also likely to be separated from residential areas by commercial and industrial zoning. Further, the helicopters routinely used by commercial flight schools, for medical evacuation, for traffic reporting, and for urban police work also tend to be smaller than those in use by the military.

As noted in Section 1.5, large civil tiltrotors are likely to operate primarily from downtown landing areas and from non-runway areas of large urban airports. The mismatches noted above in exposure conditions, residential locations, and population characteristics between large tiltrotor and general commercial helicopter cases may be great enough to call into question the generalizability of findings about the annoyance of low-frequency noise from surveys conducted near military bases and other civil helicopter operating areas to the case of present interest.

10.3.1 Construction of a searchable database

Nonetheless, it may be worthwhile to design and assemble a fully searchable database of information about U.S. facilities at which a survey of opinions concerning the annoyance caused by low-frequency, airborne noise could in principle be conducted. To minimize the costs of collecting the desired information at sites that are clearly unsuitable for interviewing on an *a priori* basis, minimal size requirements should be established for exposed populations and numbers of daily operations. For example, it could be decided to exclude from the database any site that does not expose at least 100 households within 500 m to noise created by at least 10 helicopter operations per day.

The database itself must be designed so that it can be searched by each of its substantive data fields, individually and conjunctively. A formal database design must be prepared, and a small demonstration provided of a small collection of mock information. A standard (SQL-based) implementation is strongly preferred.

For each potential interviewing site, the following information should be compiled:

Numbers of each type of helicopter based at facility
Average daily number of landings and takeoffs by helicopter type
Seasonal variations in operational rate (if any) by helicopter type
Day-to-day variations in operational rate by helicopter type
Location(s) of landing pad(s) and standard approach and departure paths
Estimated number of residential households within 3 kilometers of operating areas
Locations of other (non-helicopter) sources of low-frequency noise in vicinity of residential neighborhoods
Identification of other major sources of community noise
Contact information for responsible aviation and civil authorities

Note that the availability of HNM-created DNL contours for a facility supporting helicopter operations is not necessary, since such contours reveal little about infrasonic noise exposure.

The effort necessary to compile information for the database should be organized geographically (for example, by major metropolitan statistical area or federal region), and should include both military and civil facilities. Hazf a dozen such initial areas (for example, in the vicinity of military training bases such as Ft. Eustis or Ft. Rucker) should be identified as a starting point for filling the database.

The deliverable products of this study phase are:

1) An initial database design that identifies all of its tables, fields, and organization, and a small-scale demonstration of its implementation on a mock data set;

2) Upon approval of the formal database design and demonstration, a plan for acquiring the specified information that indicates the sources that will be used to identify potential sites and estimates the costs necessary to collect the desired information; and

3) A completed database itself containing information for at least four major metropolitan statistical areas.

10.3.2 Analyses of database

Upon completion, the initial database should be searched to prioritize potential sites at which an opinion survey similar to that described in Appendix C could be cost-effectively conducted. For initial evaluation purposes, all sites should be identified at which more than 500 households are located within 0.5 km of helicopter operating areas which support 10 or more landings and takeoffs per day. Depending on the numbers of potential sites that are identified by the initial screening, further refinements of search criteria may be warranted as well to create a prioritized list of sites worth further investigation

10.3.3 Site visits

It is likely that relatively few sites per geographic area will emerge from the above analyses. If as many as three sites per geographic area are identified, each should be visited to confirm its suitability for conduct of the desired social survey. Preparations for site inspections should begin with an examination of aerial photography, as available from Google Earth™ or similar applications. If usefully large residential areas are apparent from this imagery, radius samples centered on the operating areas should be attempted, and counts prepared of the numbers of listed telephone subscribers in at least two low-frequency noise exposure zones.

Week-long field measurements of low-frequency noise levels should be scheduled next to confirm that the exposure levels are reasonably similar to those expected from tiltrotor operations. The most important exposure level characteristics include the maximum sound level of the low-frequency content (particularly the fundamental blade passage rate and first few harmonics), and the rise and decay rates of the low-frequency portion of the time history.

It may be necessary to meet with civil or military authorities at this stage to discuss the possibility of conduct of a social survey, since it may not be possible to obtain permission to make low-frequency noise level measurements without the consent and cooperation of such authorities.

10.4 Detailed study design

If sufficient sites with appropriate low-frequency noise exposure, residential populations, and other qualifying conditions can be found, a detailed study design should be prepared to conduct interviews in accordance with the methods described in Sections 8.4 through 8.7 of Appendix D of this report.

10.5 Conduct of study

Upon approval of the study design, interviews should be conducted, analyzed, and reported as described in Section 8.8 of Appendix D of this report.

11. APPENDIX F: RECOMMENDATIONS FOR LABORATORY STUDIES OF TOLERANCE FOR INFRASONIC CABIN NOISE

11.1 Overall Technical Goals

The primary goal of laboratory study is to solicit annoyance judgments and behavioral preferences for exposure to infrasonic noise environments of the sort likely to be present in the passenger cabin of a large civil tiltrotor. However, given the substantial costs of readying a test facility for current uses, it would probably be cost-effective to test additional hypotheses as well. Secondary hypotheses which could be tested include several about the annoyance of prominent low-frequency, steady-state harmonic content of infrasonic signals in the 20 -100 Hz spectral region, and the annoyance of periodically time-varying (“throbbing”) and aperiodically (intermittently) time-varying harmonic content.

11.2 Test environment

A human-rated test facility is required in which moderately high levels of very low-frequency noise (~130 dB at 10 Hz) can be repeatedly presented to individual observers for continuous periods of an hour or more. Ambient noise levels in the facility at frequencies below 100 Hz should be no higher than about 50 dB. The test compartment must be of sufficient size and thermal mass (to counter excessive heat accumulation) to permit comfortable occupancy for durations of at least an hour. Alternatively, the compartment must be actively cooled and otherwise rendered safe for extended human occupancy. Test subjects must be free to exit the facility without external assistance at any time.

Several low-frequency test facilities of modern design (*cf.* Section 2.3) mount transducers in one airtight compartment and provide seating for one or more test subjects in an adjacent airtight compartment. A few other facilities, originally designed for other purposes, might also be adaptable for use if measures could affordably be taken to manage reverberation, improve insertion loss to the point that sounds of external origin are fully masked, and modernize signal production and control equipment.

11.3 Primary Study

The primary study is intended to determine the relative tolerance of test subjects for cabin noise environments containing varying amounts of infrasonic tonal energy. The results of the study can inform decisions about the extent of infrasonic noise control design measures that may be needed to render the cabin noise environment of a large civil tiltrotor acceptable to passengers.

Two sorts of experiments should be conducted to increase confidence in the repeatability and interpretability of findings. The first should be an adaptive paired comparison study intended to establish points of subjective equality of annoyance of a current generation commercial transport aircraft cabin noise environment with that of a large civil tiltrotor operating in both cruise and helicopter-moded.

In a single trial of an adaptive paired comparison protocol, observers listen to a pair of signals, and then decide which of the two is the more annoying. One of the signals, the

"standard", remains at a fixed level on all trials. The computer controlling signal presentations is programmed to adjust the level of the comparison signal between trials, and to continue presenting pairs of sounds until sufficient data are collected to satisfy one or more predetermined stopping criteria. The annoyance of a small number of standard signals is generally compared with the annoyance of a larger number of comparison signals. Successive trials usually interleave multiple comparisons, while the order of presentation of standard and comparison signals is randomized.

The main advantages of adaptive paired comparison testing include the face validity of annoyance judgments derived from direct comparisons of signals heard on each trial, the efficiency and cost-effectiveness of the experimental method for comparisons involving multiple test signals[35], and the direct interpretability of findings in terms of differences in sound levels necessary to render all sounds equally annoying.

The second study should rely on a behavioral "active avoidance" measure of preferences for cabin noise environments, in which test subjects are free to spend as much time as they care to in any of several alternate cabin noise environments. In such a free choice paradigm, observers press a button whenever they would prefer exposure to a different noise environment to exposure to the current noise environment. If no responses are made after a given duration of exposure (say, five minutes), the computer controlling the experiment presents a different, randomly selected noise environment. Noise environments which people strongly avoid (spend little time listening to) are assumed to be less tolerable than those to which they voluntarily expose themselves for longer periods of time. The relative tolerance of observers for noise environments can be scaled directly from the time spent listening to each.

The main advantages of behavioral free choice testing for present purposes include the unambiguous nature of the avoidance response, the similarity of experimental exposure conditions to the air traveler's passenger experience, and the complementary nature of the avoidance and annoyance judgments.

11.3.1 Test signals for adaptive paired comparison annoyance judgments

The standard (invariant) signal for this paired comparison study should be a recorded, five-second long sample of interior noise in a current generation commercial transport aircraft. The most appropriate cabin noise environment with which future tiltrotor cabin noise should be compared may be that of a short- to medium-range aircraft (such as a regional jet) with which a large civil tiltrotor might compete on domestic inter-urban routes.

As resources permit, alternate standard signals could also be considered, including the noise of a turboprop passenger cabin, or even that of a turbofan-powered longer-range aircraft. Note, however, that use of more than one standard signal has either a direct multiplicative effect on the number of judgments that observers must make, or necessitates additional assumptions about transitivity of annoyance judgments and/or a more complicated study design and analysis plan.

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[35] Any of several well-known adaptive algorithms (rules for changing step sizes between trials following successive judgments, operating points on the psychometric function, and stopping criteria) will suffice for present purposes.

A suite of about ten simulated tiltrotor cabin noise environments should be synthesized to serve as comparison signals. The "high" frequency portion (that is, the portion extending above 100 Hz) of each simulated cabin noise signal must be identical, but need not necessarily closely resemble cabin interior noise of any current production aircraft. Shaped broadband noise, similar in spectral content to that shown in Figure 83, will suffice. Figure 83 shows Boeing 737 in-cabin, one-third octave band binaurally-measured sound pressure levels at three locations during cruise conditions (Sullivan, 2009). All locations are at window seats, one in the forward cabin, one mid cabin, and one in the aft cabin. The data points present the average of left and right ear measured sound levels.

A noise spectrum suitable for paired-comparison test purposes is shown as the heavy dashed line in the figure. This spectrum approximates the shape of the measured spectra, and is flat (pink) from 80 to 250 Hz, with a rolloff of 6 dB per octave on either side of this range.

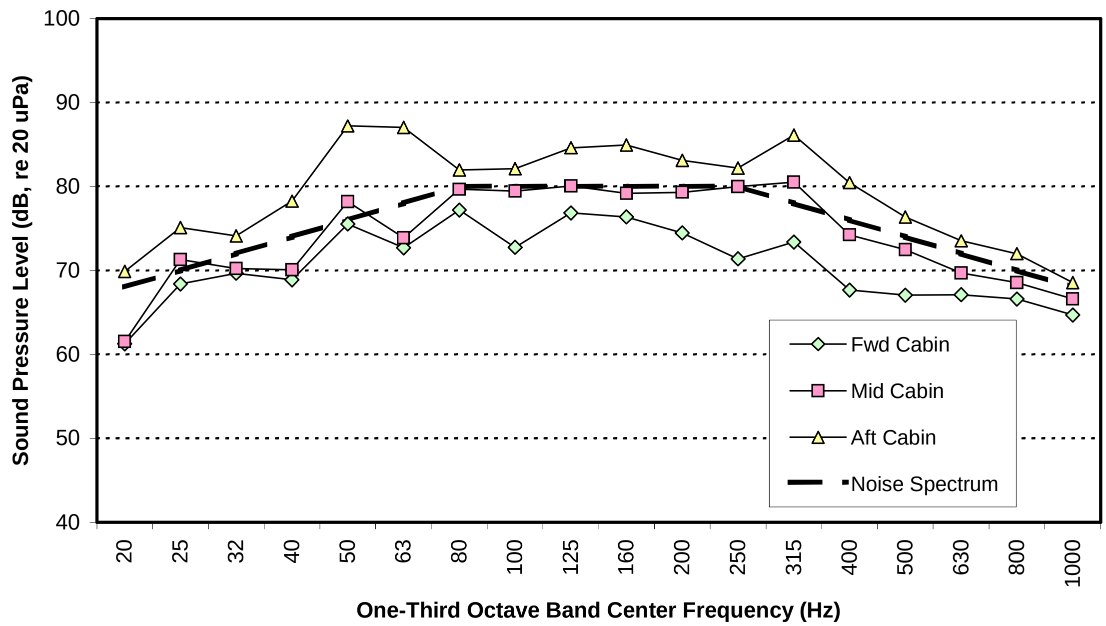

Figure 83: Boeing 737 in-cabin sound levels during cruise, and test signal noise spectrum.

At least one test signal should be constructed with infrasonic content representative of each condition seen in Table 15. The various signals should contain the main rotor blade-passage frequency and varying numbers of harmonics. They should also include for each harmonic set two different harmonic rolloff rates to cover the expected range in harmonic content in the total signal from tiltrotor aircraft.

Broadband signals with equivalent narrow band (one-third octave, or perhaps one critical band) should be constructed in order to determine any tonal "penalties" compared with broadband noise. Knowledge of such penalties will enable the reconciling of experimental results with existing workplace and residential criteria that are broadband-based.

Table 15: Recommended test signals

Signal Number	Fundamental Frequency (Hz)	Harmonic Frequencies (Hz)
1	9	None
2	9	18 (6 dB / harmonic decay)
3	9	18, 27 (6 dB / harmonic decay)
4	9	18, 27 (12 dB / harmonic decay)
5	9	18, 27, 36 (6 dB / harmonic decay)
6	9	18, 27, 36 (12 dB / harmonic decay)
7	9	18, 27, 36, 45 (6 dB / harmonic decay)
8	9	18, 27, 36, 45 (12 dB / harmonic decay)
9	9	18, 27, 36, 45, 54 (6 dB / harmonic decay)
10	9	18, 27, 36, 45, 54 (12 dB / harmonic decay)
11	Broadband equivalent to #1	
12	Broadband equivalent to #2	
13	Broadband equivalent to #3	
14	Broadband equivalent to #5	

11.3.2 Test signals for active avoidance study

The test signals for the active avoidance study should be steady-state samples of synthesized or recorded aircraft cabin noise, digitized as .wav (or in other non-lossy format) files suitable for reproduction through a 16 bit digital to analog converter. The files must either be of sufficient length to support continuous reproduction for periods of at least ten minutes, or otherwise capable of seamless looping without any audible transient. The C-weighted sound pressure levels of all signals must be adjusted to within ± 1 dB of one another as heard at the observer's listening position.

11.4 Instructions to observers

Observers must be trained for about an hour in the test protocols prior to participation in the laboratory studies. For the paired comparison testing, they should be given written instructions to read, and an opportunity to ask questions about test methods. They should then participate in at least 15 minutes of training trials to permit them to familiarize themselves with the need to respond promptly, but to wait until the second signal of each trial ends before doing so.

After the observers have become familiar with test procedures, they should be required to compare the annoyance of one of the standard signals with itself, and with any other standard signals produced for the paired comparison testing. They should also repeat at least one of the comparisons until test/re-test differences are within ± 2 dB.

11.4.1 Protocol for adaptive paired comparison testing

All aspects of test administration should be controlled by a personal computer, which can also serve as the response apparatus. The display screen should clearly indicate the progression of trial intervals, as, for example, by showing large text messages such as "Listen now to Signal

1", "Listen now to Signal 2", and "Press 1 if Signal 1 was more annoying or 2 if Signal 2 was more annoying."

The duration of all sounds to be compared should be identical. If the nominal duration of signals is four seconds, then a trial (including intra-signal and response intervals) will last approximately ten seconds. Assuming that the adaptive forced-choice algorithm will require about 12 trials per annoyance judgment, judgments of each single signal pair will require a little more than two minutes. For each hour of testing (composed of two 25 minute judgment sessions with five minute breaks), it should be possible to complete about 20 signal pair comparisons. If four such judgment sessions (two hours) can be scheduled per day, it should be possible over the course of two days for most test subjects to complete at least fifty direct comparisons of the annoyance of pairs of test sounds, including ample repeat judgments to help gauge the reliability of each observer's judgments.

11.4.2 Protocol for active avoidance testing

All aspects of test administration should be controlled by a personal computer, which can also serve as the response apparatus. The computer screen should display a text string prominently identifying the signal that is currently playing, along with a message to the effect "Press the space bar if you would rather hear a different sound". The sequence of sounds to be presented during each comparison session should be pre-randomized, subject to the constraint that all signals within the ensemble to be compared in a given session are scheduled for equal numbers of presentations[36]. Each time the observer requests a different signal, the control software should present the next sound on the list, until the test session ends when the observer has been offered equal numbers of opportunities to tolerate exposure to each signal.

The control software should also time the duration of voluntarily tolerated exposure to each signal, tally total durations of all signal presentations, and track the number of commanded and spontaneous signal presentation changes.

11.5 Observers

Informed consent should be sought from approximately 30 adults for participation in each of the two primary studies. The numerically high infrasonic sound pressure levels may complicate approval by an Institutional Review Board unfamiliar with the audibility and hearing damage risk of very low-frequency sounds. Conventional (*i.e.*, speech frequency range) audiograms should be administered prior to participation in the study, and also upon completion of participation in the study, to screen observers for hearing sensitivity within 15 dB of audiometric zero, and to document the absence of any exposure-related temporary threshold shift.

11.6 Secondary Studies

While the primary annoyance-related interest is in the simple presence of infrasonic energy in tiltrotor cabins, secondary interests include the effects on annoyance of periodic modulation

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[36] At the risk of extending testing time beyond budgetary limits, the same sounds can be scheduled for presentation at levels different (say, by ± 5 dB) from a nominal (0 dB) gain setting. Presentation of the same sounds at different levels would permit some quantitative assessment of the degree to which observers are willing to trade level for duration of exposure within signal ensembles.

and intermittency of such infrasonic energy. Reports of the annoyance of modulated ("rumbling" or "throbbing") HVAC noise are common, as are reports of the annoyance of intermittently audible infrasonic energy in community settings. Both of these issues are better addressed in the active avoidance paradigm than in paired comparison testing, because the durations of the required test signals are impractically long for paired comparison judgments.

The frequency range of interest for potential studies of effects on annoyance of periodic modulation extends from about 0.5 to 5 Hz, while the range of depth of modulation extends from about 3 to 10 dB. The only portions of these ranges that should be explored for present purposes are those that might plausibly occur in tiltrotor passenger cabins.

In one set of conditions that merits empirical study, infrasonic pulse trains at four or five levels separated by 3 - 5 dB steps should be amplitude modulated at percentages ranging from about 10% to 50%. In at least one or two conditions, the levels of the sound and of the modulation depth should bracket individual test participants' threshold of hearing at infrasonic frequencies corresponding to tiltrotor fundamental and harmonic frequencies.

11.7 Deliverables

The deliverable products of these primary and secondary study phases are one or more technical reports 1) fully describing hypotheses, test procedures and conditions, and 2) analyzing, comparing and discussing the findings of both paired comparison and active avoidance judgment studies.

During Phase 1 of the study the contractor and NASA will finalize the goals of the study. The exact experimental procedure will also be developed in consultation with NASA. A set of recommended test signals will also be prepared to meet the study goals. The entire test plan will be prepared by the contractor as a formal report for NASA review prior to undertaking the testing phase of the study.

During Phase 2 the contractor will undertake testing at NASA facilities. Test participants will be recruited and screened for normal hearing.

During Phase 3 test data will be analyzed and results discussed with NASA personnel. A draft final report will be prepared by the contractor detailing the findings of the study. After NASA review a final report will be issued.

12. APPENDIX G: RECOMMENDATIONS FOR LABORATORY STUDIES OF SPEECH MODULATION BY INFRASONIC TONES

At high enough sound levels, periodic infrasonic energy generated by passage of rotor blades during tiltrotor cruise and vertical flight regimes could impair onboard speech communication. Yeowart and Connor (1974) reported modulation of speech by very low-frequency sound at levels as low as 115 dB. Johnson (1973, *cf.* section 6.4.9 of this report) noticed voice modulation at infrasonic levels in the 120 – 145 dB range, from which he concluded that "Speech intelligibility under critical conditions under high task loading and other environmental stressors must be further studied." Evans (1976, *cf.* section 6.4.3 of this report) has noted "difficulty in speaking and voice modulation" in the range of 2 to 5 Hz at levels between 125 and 137.5 dB. Although these reports are somewhat anecdotal in nature, they merit at least informal evaluation, followed by a more rigorous examination if they prove reliable and of appreciable magnitude.

The nature and implications of potential interference with speech quality differ for tiltrotor aircrew and passengers. Speech intelligibility between cockpit crewmembers and among cockpit crew and ground controllers is on its face a more pressing concern than naturalness of vocal quality in casual conversations among passengers.[37] An appreciable impairment of the naturalness of voice quality, however, could limit the competitiveness of commercial operations of large civil tiltrotors by interfering with comfortable conversation in the passenger cabin.

The usual concern of assessments of speech intelligibility (*cf.* ANSI S3.5-1997, as revised) is determination of speech-to-noise ratios adequate to support reliable voice communication. This is solely a speech masking issue. However, a steady, periodic modulation of speech by infrasound could also degrade intelligibility via a second mechanism: rhythmic interference with speech production. Vowels would probably be less affected by such interference than shorter duration consonants. Hence, lightly modulated speech could produce odd-sounding, even if reasonably intelligible speech.

Deeper modulation might not simply yield unnatural-sounding speech, but also speech of lesser intelligibility. The combined effects of appreciable voice modulation and background noise (cabin noise in the case of passengers, or a combination of cabin noise, radio communication noise, and radio distortion products in the case of crew-to-controller communications[38]), might further impair speech intelligibility.

A simplistic simulation of the potential severity of the above effects was undertaken for present purposes by sinusoidally modulating a tone and a brief speech sample at 5 Hz, and at

[37] Note, however, that speech which is predictably modulated at infrasonic frequencies can almost certainly be processed to maintain voice quality in air-to-ground communications, and between cockpit crewmembers wearing headsets. (Efforts of a related nature to improve the intelligibility of helium speech have been fully successful.)

[38] Noise-canceling headsets can minimize the potentially adverse effect of the airborne component of on-board ambient noise, but cannot correct for radio communication noise and distortion products.

modulation depths of 6, 12, and 20 dB.[39] Modulation of the continuous tone was readily apparent in casual listening, even at the shallowest modulation depth. Due to the redundancy and inherently discontinuous nature of speech, low-frequency modulation was readily apparent in speech signals only at greater modulation depths. The combination of appreciable modulation and modest amounts of added noise was more noticeable.

The following research plan addresses the above issues on a stepwise basis.

12.1 Preliminary (Informal) Evaluation

12.1.1 Overall Technical Goals for Preliminary (Informal) Evaluation of Speech Modulation at Infrasonic Frequencies

The primary goals of preliminary investigation of speech modulation[40] at infrasonic frequencies are 1) to attempt to verify prior reports of such effects, 2) to identify approximate infrasonic frequency ranges and sound levels at which such effects may occur, and 3) to gauge whether such effects, if observed, are of sufficient magnitude to affect naturalness or intelligibility of speech.

A secondary goal is to obtain for later use a set of high quality recordings of connected discourse in the presence of periodic low-frequency amplitude modulation. If voice quality is sufficiently affected by airborne infrasound, such recordings could serve as a database for the design of signal processing algorithms to restore natural-sounding speech.

12.1.2 Approach to Preliminary Evaluation

A human-rated facility similar to that described in Section 11.2 of Appendix F of this report is required to produce reasonably well-controlled airborne infrasound with minimal higher frequency distortion products and structureborne, whole body vibration. To minimize confounding of speech intelligibility effects by extraneous masking noise, ambient noise levels in the test facility should remain at least 20 dB below speech levels within the range from roughly 100 Hz to 8 kHz. If the facility is highly reverberant at speech frequencies, it may also be necessary to construct a partial absorptive enclosure around the speaker's seating position to minimize confounding due to effects of degradation of speech intelligibility due to reverberation.

Given the informal nature of the preliminary investigation, the inability to identify in advance a fixed regimen of exposure conditions, and the intended restriction of infrasonic exposure to the

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[39] Note that this simulation does not attempt to reproduce the effects of infrasound on speech production, but only the gross effect of amplitude modulation *per se*. Amplitude modulation alone is a relatively benign transformation of speech signals that could well underestimate the effects of infrasonic modulation on speech quality, intelligibility, and ease of conversation aboard a large civil tiltrotor.

[40] In common assessments of the effects of modulation on speech quality, the issue of concern is the effect on speech intelligibility of temporally fluctuating speech-to-noise ratios. The issue of concern in the present case is that of fluctuations in speech levels caused by periodic, involuntary interactions of intense (even if not necessarily audible) infrasonic tonal energy with vocal tract mechanisms in otherwise constant background noise in the speech frequency range.

Principal Investigator, it is neither necessary nor desirable to attempt to obtain informed consent for participation by human subjects from an Institutional Review Board (IRB).

Instead, the Principal Investigator should prepare a signed statement for an IRB indicating the voluntary and unpaid nature of the exposure, and the approximate range of anticipated exposure conditions. The statement should also indicate the intent to avoid painful, prolonged (>10 minutes), extreme (>140 dB), or otherwise intolerable exposure levels during any single exposure condition. The principal investigator should directly control all exposure frequencies and levels, and be provided with a deadman switch that will immediately terminate infrasonic exposure when released. Audiograms should also be taken before exposure to infrasound, and upon completion of all exposure conditions

The principal investigator, seated in the test facility, should read aloud a passage lasting about five minutes from a newspaper or similar non-technical material, in a conversational manner. The speech samples should be digitized and stored in a lossless (*e.g.*, .wav) format, and monitored electronically in real time over a high quality reproduction system by at least two listeners in a quiet listening area outside the test facility. At the start of each passage, the principal investigator should announce the frequency and level of infrasound during the subsequent reading. The listeners should rate the "naturalness" (fluidity, cadence, continuity, pitch, timbre, quaver/tremor, pronunciation, and apparent level of vocal effort) of the real-time speech for each five-minute passage.

A method of limits approach should be adopted for scheduling exposure conditions, in level increments of 10 dB and frequency increments of one octave, starting at 100 dB and 5 Hz, as suggested in Table 16. If no obvious impairment in speech quality is noted over the range of frequencies and sound pressures tested, no further investigation may be warranted. (Recall that the overall goal is not to determine whether speech modulation occurs at *any* combination of frequencies and sound pressures, but whether it occurs at levels that can realistically be expected to occur in a commercially viable tiltrotor.)

Table 16: Infrasound exposures for speech sample recording

EXPOSURE CONDITION	FREQUENCY (Hz)	SOUND PRESSURE LEVEL (dB)
1	5	100
2	5	110
3	5	120
4	5	130
5	10	100
6	10	110
7	10	120
8	10	130
9	10	140
10	20	110
11	20	120
12	20	130

If the intelligibility or naturalness of a recorded speech sample is considered to be noticeably impaired in any exposure condition, no further informal evaluations should be performed at the same frequency. Instead, a more detailed evaluation should be undertaken, as suggested in subsequent sections.

If no appreciable adverse effects on speech quality or intelligibility are noted under the exposure conditions described in Table 16, broadband noise characteristic of aircraft cabins should be added to the recorded speech samples, and the listening tests repeated. Background noise should be added at a minimum of two speech-to-noise ratios: 0 dB and -5 dB. If no meaningful effects are observed in either of these noise conditions, no further evaluations are recommended.

The deliverable product of this study phase is a letter report 1) documenting the nature of the informal assessments and the range of exposure conditions explored, and 2) summarizing the observations of the speaker and listeners.

12.2 Follow-up Informal Evaluations

If listeners (including the principal investigator) agree that the naturalness or intelligibility of speech is noticeably impaired in any exposure condition, a more thorough investigation should be conducted of the range of frequencies and exposure conditions under which such effects occur. With IRB approval, samples of connected discourse from several additional male and female speakers should be collected; judgments of the naturalness of the samples should be solicited from additional raters; and the effects of intermediate levels (at 5 dB intervals) and frequencies (at one-third octave band intervals) should be explored.

Speech intelligibility index (SII) calculations per ANSI Standard S3.5-1997 should also be performed for several of the speech samples over a 20 dB range of signal-to-noise ratios as heard in several extant aircraft cabin noise environments. The intent of such calculations is not to document that impairments of the naturalness of speech are necessarily accompanied by reductions in speech intelligibility, but rather to confirm the independence of the judged naturalness and intelligibility of natural speech.[41] (In other words, some changes in either the naturalness or the intelligibility of the modulated speech may not be accompanied by any change in the SII.) If the follow-up evaluations also reveal no appreciable effects, no further formal analyses are warranted.

The deliverable product of this study phase is a second letter report 1) describing the range of infrasonic exposure conditions investigated and the nature of any observed impairments of intelligibility and/or naturalness of vocal quality, and 2) summarizing the values of SII in the exposure conditions of interest.

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[41] Purely acoustic methods of assessing speech intelligibility, such as ANSI Standard S3.5-1997, pertain only to natural speech, and can not reliably estimate the intelligibility of systematically distorted (*e.g.*, time-reversed) speech. Methods of assessing speech intelligibility that involve judgments made by panels listening to actual speech samples are more appropriate for present purposes.

12.3 Formal Evaluations of Effects of Infrasonic Speech Modulation

If the informal preliminary evaluations reveal noticeable degradation of either the naturalness or intelligibility of speech modulated by airborne infrasound, a series of more formal evaluations should be undertaken to improve systematic understanding of such effects, and to quantify their nature and magnitude.

Due to the potential subtlety of speech modulation effects, measures of percentages of syllables correctly understood may not yield the most sensitive indications of the effects of infrasonic tonal energy on speech quality. Listening tests involving connected discourse (at a minimum, carrier phrases) are preferred to tests relying on phonetically balanced word lists. At 5 Hz, for example, modulation may affect only a few syllables, such that sentence intelligibility could remain high even though speech itself could sound unnatural.

Two evaluations by panels of ten listeners are suggested: (1) a rating of speech naturalness, and (2) a rating of conversational ease.

12.3.1 Ratings of naturalness of speech

A panel of ten listeners should make pair-wise comparisons of the naturalness of ten-second long samples of speech recordings. The instructions should request panel members to judge whether the first or second sample heard during each trial is the more natural sounding. Comparisons should be made between unmodulated speech and each recording made under the exposure conditions described in Section 12.1.2. Each comparison should be repeated once, with the standard signal (unmodulated speech) heard once in the first and once in the second presentation intervals.

The panel should be seated in a quiet, relatively small, normally reverberant room, facing a loudspeaker. All seating positions should be within about ten feet of the loudspeaker. In the interests of simplicity and expedience, an experimenter may manually control the presentation of signal pairs, and listeners' responses may be recorded with pencil and paper. All signal presentations should be made at a fixed A-weighted sound pressure level of approximately 75 dB. The broadband ambient noise level in the test environment should not exceed about 50 dB, and should not include any prominent tones or narrow bands of noise.

12.3.2 Ratings of conversational ease

In part because speech production and speech understanding are highly over-learned skills, speech intelligibility degrades only slowly as speech quality and listening conditions worsen. Thus, even if it is found that exposure to infrasonic tones at realistic levels leads to unnatural-sounding speech, it may be difficult to document such effects solely in terms of intelligibility. In particular, common measures of speech intelligibility such as those identified in ANSI S3.5-1997 and ANSI S3.2-2009 (describing calculation of the Speech Intelligibility Index and evaluation methods such as the Diagnostic and Modified Rhyme tests) and phonetically balanced word lists, are likely to be relatively insensitive to decreases in speech quality and conversational ease associated with infrasonic modulation of speech under realistic exposure conditions.

Periodic, low-frequency modulation of speech levels at realistic modulation depths is not likely to have a major adverse effect on speech intelligibility. It may, however, have a greater effect on the effort required and hence willingness to participate in casual conversation. Thus, the greater attention needed to adjust to degraded but still intelligible speech could discourage

cabin conversation, and thus perhaps the commercial prospects of civil tiltrotors. It is therefore suggested that a panel of listeners rate the ease of understanding of one-minute samples of connected discourse.

Scripted one-minute long conversations between adult male and female native English speakers should be recorded in the presence of infrasonic tones at levels and frequencies characteristic of expected in-cabin levels in a large civil tiltrotor (*cf*. Section 1.3.8). Three such conversations, each involving different speakers, should be recorded at each combination of levels and frequencies of interest.

A panel of ten adult, native English speaking listeners should make absolute judgments about the ease of understanding each conversation on a five point scale under the listening conditions described in Section 12.3.1. The scale categories should be "no difficulty understanding conversation", "conversation is slightly difficult to understand", "conversation is moderately difficult to understand", "conversation is very difficult to understand", and "conversation is extremely difficult to understand".

12.4 Deliverables

The deliverable product of this study phase is a technical report 1) describing the range of infrasonic exposure conditions investigated, 2) the methods employed to solicit the ease of understanding judgments, and 3) any meaningful differences in median and mean ease of understanding judgments attributable to infrasonic exposure conditions.

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This report reviews the English-language technical literature on infrasonic and low-frequency noise effects; identifies the most salient effects of noise produced by a future large civil tiltrotor aircraft on crew, passengers, and communities near landing areas; and recommends research needed to improve understanding of the effects of such noise on passengers, crew, and residents of areas near landing pads.

15. SUBJECT TERMS
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